The Human-Machine Interface (HMI) and Re-bar Detection Aspects of a Non-Destructive Testing (NDT) Robot

by

Julian Chua Ying Kit (BSc.)

City University

This thesis is submitted for the Degree of Doctor of Philosophy

Department of Civil Engineering

October 1996

I dedicate this thesis to my

grandmother.

Contents

Conclusion

Appendices

Acknowledgments

Denis Chamberlain	City University	Proposing the research project, supervising my work and proof reading it.
EPSRC	Formerly SERC	Funding and grant.
John Alldred	Protovale Ltd.	Providing a CM5 covermeter for research purposes and providing assistance in the automation process of the covermeter.
John Reilly	City University	Assistance in building PCB boards for data acquisition purposes.
Jim Hooker	City University	Assistance with photography.
Alastair Paterson	City University	Assistance with Windows programming.
Shereen Akrawi	City University	Encouragement and friendship.
Rushna Begum	City University	Encouragement and friendship.
Wendy Chan		Encouragement, friendship, keeping me fed and love.
My Parents		Encouragement, support and love.

Declaration

"I grant powers of discretion to the University Librarian to allow this thesis to be copied in whole or in part without further reference to me. This permission covers only single copies made for study purposes, subject to normal conditions of acknowledgment."

Abstract

The Construction Industry is for the greater part unfamiliar with the operation of automation and robotics devices. Furthermore, the extent to which the existing labour force can be re-trained, or be justifiably supported by specialist personnel, remains unclear. Arising from this, it is thence clear that the quality of the human interface or the so called Human-Machine Interface (HMI), will be a decisive factor in the successful introduction of new devices. In view of this, it is therefore, somewhat surprising that a review of current HMI's for built construction tasking devices point to few instances of well founded provisions. In the majority of cases and characteristics of the HMI more closely relate to the basic functionality of the device, its motion control etc., then more relevant, human cognizance.

There are two main objectives to this research. The first objective is to research the factors which influence the effectiveness of the HMI provisions for operators of robots and to devise guidelines for their development, and apply these in a demonstrator application for a building inspection robot. There are many factors to consider in the provision of an effective HMI, including compatibility with the cognitive characteristics of operators, selection of useful analogies and metaphors, navigational system employed, encourage exploration, informative feedback, consistency, directness in interaction, place operators in control, terminology, and the use of colour, geometry and spatial layout. The wide spread use of colour is particularly interesting in that it has been known for more than a decade that abuse of colour can lead to operator distress and drastically reduced productivity in the involved activity.

The second objective is to automate a covermeter to such an extent as to be able to obtain mappings of embedded re-bars, their size estimates, and depth-of-covers. The research looks at current methods of estimating the latter two unknowns, and proposes a more effective method for automation. The method is based on analyzing the traverse profile from a covermeter scan across the involved re-bars.

1. Introduction

The developments in this thesis contributes in part, to a current project at the Construction Robotics Unit (CRU), City University, London. The CRU is developing a robot called CURIO (City University Remote Inspections Operations), to be used in performing various non-destructive inspections on tall structures (Chamberlain & Bleakley, 1994). The different developments underway for this project, are described further in Appendix A, while Appendix B provides a description on the robot. The author's research contributes to two areas of the CURIO project. The first area concerns the development of the Human-Machine Interface (HMI) command center for the remote control of CURIO. Factors that influence the effectiveness of the HMI provisions are investigated, and guidelines for its development worked out and applied. The second area of this project researches the automation and computerization of a covermeter with a robot. The development involves the estimation of both re-bar sizes and depth-of-covers from investigating a covermeter traverse profile reading. The computerization of the covermeter is also a precursor to the automation of other non-destructive test (NDT) equipment, to be implemented on the robot.

1.1 Defining HMI

The term "Human-Machine Interaction" (HMI) is frequently used interchangeably with other terms such as "Human-Computer Interaction" (HCI), "Computer-Human Interaction" (CHI), "Man-Machine Interaction" (MMI), "Man-Machine Systems" (MMS), "Man-Computer Dialogues" (MCD), and even the word 'interaction' itself is interchangeable with the word 'interface'. They all essentially mean the same thing, as explained later. This thesis, however, uses the preferred term 'HMI' throughout, as it is more generic in nature. The 'H' in HMI is preferred as it is not gender specific. The 'M' in HMI refers to

'Machine,' which means it is not constrained to being any one particular device. Machine could refer to any machine in general, including computers and robots. As this work refers to these items frequently, the term 'HMI' was found to be suitable and convenient.

HMI is the study of how people interact with machines to bring about, from given inputs, some desired outcome within the constraints of the given environment. It involves the study of task-oriented dialogue between people and machines. It is a multidisciplinary subject in that it draws knowledge from areas such as computer science, engineering, art, physiology and psychology. The study intends to lead to the development of practical guidelines and methods of achieving the ultimate goal of seamless interaction between a human and a device. The study, therefore, considers practically every aspect of humans. It includes the study of sight, auditory, tactile and cognitive processes of people. Even the other two human senses of smelling and tasting receive some attention. However, as much is yet to come out of research in the uses of the other three commonly used senses, sight, sound and touch, this research will be confined to them.

1.2 The Importance of HMI Studies

Originally, most operators of computer systems were themselves programmers and designers of the system. To these individuals, the applications they use would seem straight forward and easy enough to use. They would have immersed in the same conventions and culture as the individual who designed it. These individuals would normally be found in universities, research centers and the larger industries who could afford the systems. In contrast, today we find computers in smaller industries, offices, homes and even in the street. This is attributed to the rapid developments made in computer technology, huge cost reductions of these systems, ever increasing reliance of computers in the work place and the wider acceptance and greater interest of the public.

In the work place, efficiency and effectiveness of employees are of the utmost importance. Poor performance of operators on computer systems have been shown by Eason et al., to be linked to poor user interfaces (Eason, Damodaran, & Stewart, 1975). Poor user interfaces can lead to stressed users, lower work rates, decreased job satisfaction and even high absenteeism. When products do not work the way users expect them to, users get extremely frustrated and upset. It is this factor, which dictates if a system will continue to be used.

Computer companies have known this fact for some years. They now attempt to distinguish their products from their competitors by providing advertising reviews on how easy they are to use and learn. Microsoft, one of the giants in the software industry believes that the value that customers place on product usability is a key to sales success. Microsoft's latest advertising slogan is "Making it easier." The computing industry has been using similar slogans for some years to market and sell their products. In the words of Jim Seymore (1992), "Looking back, I want to suggest that 1992 was The Year of Usability. Certainly this was the year that vendors talked a lot about usability. The whole notion of usability is simply a 1990's restatement of the old ease-of-use argument that has wound throughout the history of the PC hardware and software business."

How do we define usability? Shackel (1984) has categorized usability into the following four areas: learnability, effectiveness, flexibility, and user attitude. Products should be intuitive to use. This is commonly achieved by providing an effective mental model for the user on how the product operates. The user possessing this mental model gains a high-level understanding of how things work, and is able to perform tasks and solve problems faster and more effectively than without such a model.

A product becomes user-friendly when it is quick and easy to learn without having to constantly refer to documentation, easy to relearn when not used for some time and easy to unlearn or transfer training to other products with similar features. It should encourage exploration of product features without causing fear of harm to the product. For example, the product might have an undo feature for undesired mistakes. The product should be easy to support and put right in the event of any mishap. It should also be easy to integrate into existing activity. And lastly, but definitely not least, it should give users good satisfaction in terms of their achievement and the performance of the system.

1.3 Evolution of HMI

The history of HMI has its roots in centuries of studies in the fields of philosophy, physiology, medicine, psychology and especially ergonomics. With the exception of ergonomics, these disciplines established their modern forms in the 18th or 19th centuries and in the early part of the 20th century. Ergonomics, however, had its beginnings primarily with the military in countries such as the UK and the US during World War 1 and more significantly in World War 2. Table 1.1 depicts a 30 year timeline of major events that contributed to the growth of attention to ergonomic aspects of HMI (Shackel, 1991).

Referring to Table 1.1, the development of HMI can be seen to be closely related to the development of computers, from the mainframes of the 1960's to the present day microcomputers. With the advent of microcomputers in 1978, more and more users were not typical of those of the 1960's. Users in the 1960's were mainly specialists and were often directly immersed in the same conventions and culture as the individuals who designed the mainframes. Users in the 1980's, however, came from very diverse backgrounds and often had not the technical expertise of those users in the 1960's. To make computers viable for office workers in the 1980's, computers had to be made simpler to use.

Additionally, users of the 1980's had a choice of using applications developed for the microcomputer and such, demanded applications that were more usable. The greater demand for usability in the 1980's has made a significant impact to the growth of attention to ergonomic aspects of HMI (see Table 1.1).

Table 1.1 Growth of Attention to Ergonomics Aspects of Human-Computer Interaction, modified version of Shackel's (1991)

Decade	Year	Events
1950's & 1960's (growth period of mainframes)	1959	1st recorded paper in the literature (Shackel 1959 as reported by Gaines 1985)
	1960	Seminal paper by Licklider (1960) on 'Man-Computer Symbiosis'
	1969	1st major conference ('International Symposium on Man-Machine Systems')
	1969	*International Journal of Man-Machine Studies started*
1970's (growth period of mainframes and mini-computers)	1970	Foundation of HUSAT Research Centre, Loughborough University
		Foundation of Xerox Palo Alto Research Centre (PARC)
	1970-73	4 seminal boooks published (Sackman,1970; Weinberg,1971; Winograd,1972; Martin, 1973)
	1976	NATO Advance Study Institute on 'Man-Computer Interaction'
1980's (growth period of micro-computers)	1980	Conference and book on 'Ergonomics Aspects of Visual Display Terminals' (Grandjean & Vigliani 1980) Three other books (Cakir et al, Damodaran et al, Smith & Green)
	1982	*Journal Behaviour and Information Technology* started
	1982 to 1984	7 major conferences held in USA, UK, Europe with attendance ranging from 180 to over 1000 with an average of nearly 500
	1983	Europen ESPRIT and British Alvey programmes begin
	1985	Journal *Human-Computer Interaction* started
	1985	ESPRIT HUFIT Project No. 385 begins 1 December
	1985	From 1985 the conferences of national societies ACM and BCS, on CHI and HCI respectively, become annual
	1986	Three HCI Centres launched in the UK under the Alvey initiative
	1987	Second IFIP INTERACT International Conference on HCI
	1988	Major Handbook on HCI published (ed. M. Helander 1988)
	1989	IFIP establishes Technical Committee on HCI (IFIP TC 13)
	1989	Journal *Interacting with Computers* started
1990	1990	Attendance at ACM CHI Conference reaches 2,300
	1990	Third IFIP INTERACT International Conference on HCI

Papers on the subject of HMI were very scarce in the 1950's and 1960's (Gaines, 1985; Nickerson, 1969). The first recorded papers on the subject are by Shackel on 'Ergonomics for a computer' in 1959, followed closely by Licklider's paper on 'Man-Computer Symbiosis' in 1960. The late 1960's saw the first conference on this subject (International Symposium on Man-Machine

Systems, 1969) and also the commencement of the first International Journal of Man-Machine Studies, the first HMI journal to be published.

1970 saw the establishment of two research groups that have made tremendous contributions to the development of HMI, namely HUSAT and PARC. The HUSAT group is based at Loughborough University in the UK. Though not specializing in computer-related issues, it has made substantial contributions to that field. The famous Palo Alto Research Center (PARC), a subsidiary of Xerox is based in California, USA. Xerox, a world leader at developing copying machines, setup PARC to chart Xerox's course into the electronic office envisioned for the 1990's. Some of what developed at PARC was based on earlier work by Douglas Engelbert at Stanford University. Engelbert was the first computer scientist to establish a close focus on the usability of computer interfaces (Cringely, 1996). His vision was that if computers were more user friendly, more people would be able to use computers and obtain better results. Research at PARC led to the development of the STAR workstation. Several features found on the STAR workstation, like the mouse and a desktop iconic GUI, turned up two years later in Apple's Lisa and eventually, Macintosh computers.

The 1980's began with the publication of five influential books on HMI which, to this day, are still relevant and practical (Shackel, 1991). The names of the authors are provided in Table 1.1, with full references provided in the References. Referring to Table 1.1, the growth of attention to HMI studies can clearly be seen to have increased substantially in the 1980's. This development is reflected in the number of conferences and meetings, journals, books and society groups. Table 1.1 lists the number of papers published in conference proceedings during the 1980's.

Table 1.2 Number of published papers in conference proceedings during the 1980's

Year	Conference	Papers Offered	Papers Accepted
1981	Human Factors Society	-	32
1983	Human Factors Society	-	71
1983	Association for Computing Machinery (ACM) CHI'83	130	58
1984	Human-Computer Interaction - INTERACT'84	282	180
1987	Human-Computer Interaction - INTERACT'87	375	231
1990	Human-Computer Interaction - INTERACT'90	500	312

The best evidence of growth of work in HMI must come from the stored documents in the HILITES (Hci Information & LITerature Enquiry Service) database. The HILITES database is part of a professional information storage and retrieval system setup at Loughborough University by the ALVEY Scottish HCI Centre. The database contain full references, often with abstracts to documents. Table 1.3 lists the number of documents by source year produced since 1976. The number of documents by source year available on the database, shows an exponential growth rate. The total number of different documents available in the HILITES database in 1993 reached close to 33,000 (Tomkins, 1996). This makes about 16250 new documents since 1989, almost the same figure for the whole period between 1976-1989.

Table 1.3 Number of documents by source year in the HILITES database

Documents by Source Year										
Year						1975	76	77	78	197 9
Docs						-	2	11	31	37
Year	1980	81	82	83	84	1985	86	87	88	198 9
Docs	81	119	173	338	583	530	1638	2550	456 1	609 7

1.4 HMI Considerations in the Construction Industry

The awareness of effective HMIs in automation and robotics for the Construction Industry is growing (Appendix G). However, there is still very little evidence of their implementation in such technologies. Conferences in this industry still tend to concentrate on the functional aspects of automation or robotization. As such, the author has only come across two papers in this field, which discusses in considerable length HMI/ MMI related issues (Collie et al., 1991; Fink et al.,1996). In the words of Fink et al. (1995), "looking at the current state man-machine interfaces for heavy duty construction or mining machinery, it is quite obvious that user interfaces are equipped with a fairly poor set of instrumentation." The HMI developments presented in this thesis are aimed at augmenting this.

1.5 Recent Research Areas with Covermeters

Recent research with covermeters can be divided into two main areas. The first area is in the automatic determination of both re-bar sizes and depth-of-cover values (Whittaker, 1987; Ricken et al., 1995, Chua et al., 1995), while the second area is in the provision of a visual representation of embedded re-bars (Whittaker, 1987). At the conclusion of the author's research, it became apparent that other researchers were also engaged in similar investigations (Ricken et al., 1995; Pöpel et al., 1995; Gaydecki et al, 1995), though not on the strict HMI issues.

The author's work covers both of the main areas. A new re-bar sizing and depth-of-cover determination method is introduced, and verified. This exploits the precise traverse capability of the intended robotic handling system. In Chapter 9, it is compared with methods by others. The author employs a robot in obtaining this position, while Ricken et al. (1995) employs a probe head with an optical position detector. The latter is manual in operation, while the former has been automated with a robot. The detail of the underlying algorithm is presented in Chapter 10.

On the second area, the visual representation, Whittaker (1987) and Gaydecki et al. (1995) both employ image manipulation methods to generate a more accurate mapping of embedded re-bars. Pöpel et al. (1995), however, employs a radar system with a covermeter, to visually depict the location of re-bars. Ricken et al. (1995) and the author, plots covermeter readings directly with position of the covermeter probe head. However, in the author's work, the display is the outcome of post processing the raw data to a scaling effect with representation of re-bar size, location, and depth-of-cover.

1.6 Research Objectives

The main objectives of this research are to develop a HMI command center for the remote control of the CURIO robot, and the computerization of various NDT devices. With respect to the latter, a covermeter is to be automated with a robot. The sub-objectives of the research can be identified under three main parts:

Part 1 - General HMI Goals:

1. Research the factors that influence the effectiveness of the HMI provisions, and produce guidelines for their implementation.
2. Investigate current input and output devices, their influence on HMI design, and their task suitability.

Part 2 - Covermeter Automation Goals:

3. Investigate existing, or new methods of automating a covermeter in conjunction with a robot.
4. Devise a method to accurately locate the spatial position of detected re-bars in 3-dimensions (x, y, c). Depth-of-cover (c), estimations should fall within the limits set by the British Standard, BS1881:Part204.
5. Devise a method to reliably estimate re-bar size. Accuracy should again, fall within the limits set by BS1881:Part204.

6. Investigate a method of automating the inspection process as far as possible, to achieve a method that is faster, thorough and more reliable than is humanly possible.

Part 3 - CURIO HMI Goals:

7. Build an application based on the developments of Part 1 and Part 2.
8. Achieve a transparent, intuitive HMI.
9. Investigate a method to prevent collision during an inspection process, thus reducing any fears the operator might have of damaging the system, and thus encouraging exploration of the system.
10. Investigate how the other NDT devices will be automated, and incorporated into the HMI.

1.7 Thesis Structure

The work in this thesis is divided into three main parts, as discussed in the previous section. Part 1 researches the developments in HMI, and concludes guidelines for their implementation in interface design. As psychology is the groundwork from which HMI stems, the author begins by looking at this area (Figure 1.1). The layout of the rest of the topics covered in this part of the thesis, is based on the 'iceberg' chart attributed to scientists at Xerox Palo Alto Research Center and to D. Liddle, head of Metaphor Computer Company (IBM CUA Guidelines, 1992). This iceberg is described further in Chapter 3 (Section 3.4). The 'iceberg' chart has been modified in this chapter to depict the coverage of the thesis, see Figure 1.1.

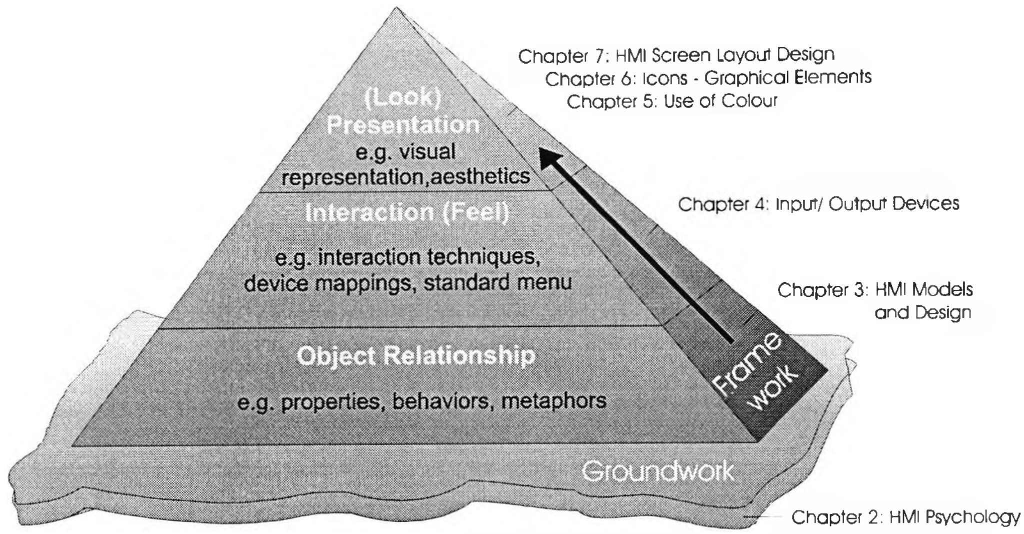


Figure 1.1 Thesis Structure (Part 1)

The structure of this thesis takes a bottom up approach to design (Figure 1.1). Individual objects and their relationship to each other (Chapter 3) are looked at first, then the interaction feel of the application (Chapter 4), and finally the presentation of the application (Chapter 5-7). Based on this method of design, Chapter 3 begins with discussions on object relationships, covering such areas as metaphors and navigational systems. Chapter 4, moves the discussion a stage up the iceberg, by investigating current and future, input and output technologies. Such technologies do, and will, effect how operators interact with machines, which in turn effects the style of an interface design. The next three chapters (Chapters 5 to 7) discuss the presentation of a HMI, and covers such issues as colour, icon design, and screen layout design.

Part 2 of this thesis deals with topics concerning covermeters, and how they can be automated with a robot. Chapter 8, the first chapter of this part, provides an overview of current covermeter designs. It also discusses how covermeters are currently employed in the inspection process. Chapter 9 discusses four manual techniques of estimating re-bar sizes, and hence, corresponding depth-of-cover values. These in turn are investigated for their feasibility in automating with a robot. A new method is also introduced, which exploits the motion control of automation. The theory and verification experiments for this new method are discussed in Chapter 10. In Chapter 11, Part 3 of this thesis, the work in Part 1 and Part 2 are integrated for the development of an application for CURIO. This chapter also discusses methods for automating the other NDT devices discussed in Appendix C. Finally, Chapter 12 presents conclusions and recommendation for further work.

2. HMI Psychology

2.1 Introduction

This chapter examines cognitive psychology that is relevant to Human-Machine Interaction (HMI) and covers the groundwork for some of the HMI guidelines found in this thesis. The chapter starts with the fundamentals of the human sensory system, how this relates to the brain, and eventually to the perception and understanding of information received. A discussion of perceptual organization and depth perception are discussed. Their relevancies is demonstrated in Chapters 6 on Iconic Design, and Chapter 7 on HMI Screen Design.

An investigation is also made into human memory. It's strengths and limitations are discussed, followed by coverage of how computer programs can be designed to complement users. The cognitive processes and how they interact with the computer processes are discussed in the previous chapter.

2.2 Perception

The process through which sensations are interpreted in light of knowledge and understanding of the world, so that they become meaningful experiences, is known as perception. The process itself, relates new experiences with old experiences and expectations (Bailey, 1982). Perception is therefore, not a passive process of simply absorbing and decoding incoming sensations. Instead, the human brain takes in sensation, and with it, creates a coherent understanding of the world. Perception creates people's experiences of the world as an organized, recognizable place. By shaping experience, perceptions influence thoughts, feelings and actions.

However, the sensation and perception processes do overlap. The sensory processes, do some primary interpretation of what it senses about the world, highlighting certain features and therefore, providing them with greater emphasis. For example, sensory cells in human retina emphasize edges and changes, to produce more contrast than the physical stimulus actually provides. Thus, interpretation of a stimulus begins even before information about the stimulus reaches the brain. Perception appears to give meaning to the stimulus that it receives from the accessory structures, based on existing knowledge and understanding of the world.

There are six well accepted features to human perception (Bernstein et al., 1991). First, perception is generally *knowledge based* (based on prior knowledge). Second, perception is often *inferential*; as we do not often need to receive the complete sensory information for the human brain to come to understanding of an experience. Third, perception is *categorical*; as people generally categorize items based on commonality of features. Fourth, perception is *relational*; in that the categories of an object would relate to one another in a consistent manner. Like, a chair would have four legs, a seat and back rest. Fifth, perception is *adaptive*; as it allows one to focus on the most important information needed to handle a particular aspect. Sixth, perception happens *automatically*. People do not have to consciously think about a particular thing or event to have perceived it.

2.2.1 Principles of Perceptual Organization

There are two basic principles of perceptual organization - figure ground perception and grouping (Bernstein et al., 1991). When a person looks at a complex visual display, they will automatically pick out certain objects to be figure while subconsciously, relegating the rest into the background. When a new object appears in the middle of the display, it becomes the focus of attention, i.e., figure, thereby, causing the rest of the display to recede into the background, i.e., ground. This process of relegating elements to be figure or ground, is call figure ground perception.

The relationship between figure and ground however, is not always clear, as Figure 2.2 demonstrates. By looking at the figure, we can continuously see two faces, then a vase and then the two faces again. There is this repeated figure-ground reversal, though it is not easily perceivable that one can see both a vase and two faces at the same time. Perception is therefore, an active process and a categorical one, as the perception of Figure 2.2 would give either the two faces or a vase at any one time, and rarely both simultaneously.

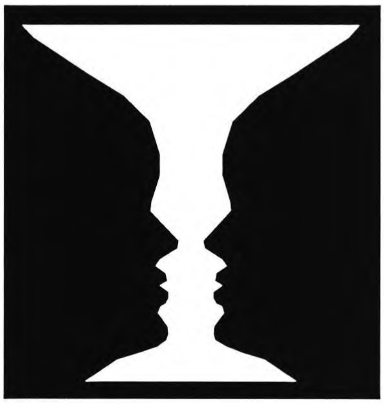


Figure 2.2 Figure ground perception

The reason why certain inherent properties of stimuli lead people to group them together, more or less automatically is explained by Gestalt psychologists (Bernstein et al., 1991). They argued that the relationship among components, rather than their fixed characteristics, determines what is perceived. Thus a person perceives a whole or pattern that may be more than the collection of individual elements. These Gestalt psychologist proposed a number of principles that explains how the perceptual system tends to connect the raw stimuli together in particular ways, organizing them into shapes and patterns. These grouping principles include:

1. *Proximity* - The closer the proximity of objects are to one another, be it in space or in time, the greater is the tendency to group them together as a unit. The effect of proximity is illustrated in Figure 2.3(a).
2. *Similarity* - Similar elements are perceived as belonging together. The effect of similarity is illustrated in Figure 2.3(b).
3. *Continuity* - Elements that appear to create a continuous form are perceived as belonging together (see Figure 2.3(c)).
4. *Closure* - Human perception tends to fill in missing contours to form a complete object (see Figure 2.3(d)).
5. *Orientation* - Human perception tends to group elements with the same orientation together. (see Figure 2.3(e)).

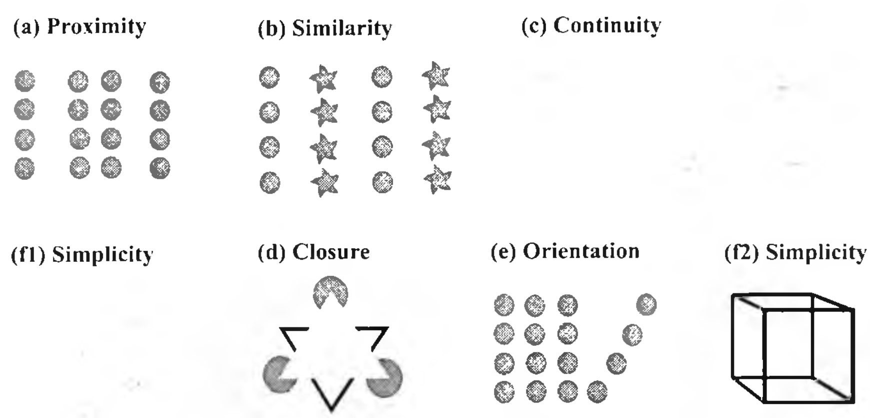


Figure 2.3 Perceptual grouping. Note the two (f) images (f1 & f2) have been separated to eliminate the effects of context

6. *Simplicity* - Human perception tends to group features in a way that makes the element simple to interpret and describe. Consider, for example, what it takes to describe each pattern in Figure 2.3(f). The figure on the left can be described as either a hexagon or a three-dimensional cube of equal sides, viewed from a certain unusual angle. In this case, the hexagon will usually prevail as it is mush simpler to describe. For the second figure, on the other hand, the two-dimensional interpretation is not as simple to describe, because the shape is no longer a simple hexagon. The simplest

way to describe it would be "two overlapping squares with lines connecting their corresponding corners." The three-dimensional interpretation of a cube is now a simpler and more naturally perceived.

7. *Common fate* - Elements that move together, at the same time and in the same direction are perceived to belong to the same unit.

2.2.2 Perceptual Constancy

Perceptions tend to rely on an objects' properties than sensory stimulation. Once an object has been perceived as an identifiable entity, it tends to be seen as a stable object having permanent characteristics, despite variations in its illumination, the position from which it is viewed, or the distance at which it appears. As an example, an object's perceived height remains constant even though the retinal image size changes as one approaches the object. From experience, most objects do not suddenly change size unless they can be inflated like a balloon. This knowledge helps humans perceive objects as being constant in size even when the retinal image size of that object changes. Size constancies can therefore be attributed partly to existing knowledge or experiences. Another reason for size constancy, is that perception is relational as the retinal image is interpreted in relation to perceived distance. As an object moves closer, its retinal image increases, but the perceived distance decreases at the same rate, therefore creating a constant perceived size.

2.2.3 Depth Perception

Depth perception gives humans the ability to judge the distance between them and an object being observed (absolute distance) and the perception of objects from one another (relative distance). Since three-dimensions cannot be reproduced on the two-dimensions of the retina's surface, the question arises of how to explain accurate human and animal depth perception. According to the classical theory of perception advanced by the German physiologist and physicist Hermann Ludwig Ferdinand von Helmholtz in the mid-19th century, depth perception (as well as constancy and most other precepts) is a result of an individual's ability to continually synthesize past experience and current sensory cues. Therefore, depth cues such as those listed by Leonardo da Vinci; linear perspective, occlusion of a far object by a near one and increasing haze as objects become more distant are used as cues in perceiving depth. These depth cues were learned as a baby when first learning how to move around in the world. In fact, people are unlikely to be aware of perceptual cues at all unless they have read about them or unless they create an inaccurate or distorted view of reality.

A more comprehensive listing of depth cues composed by the author, is provided below:

1. *Linear perspective* - The closer two converging lines are, the greater the perceived distance.
2. *Interposition* - Closer objects obscure the view of objects farther away.
3. Haze - As in reality, reduced clarity is interpreted as a cue for greater distance.
4. *Relative size* - if two objects are assumed to be the same size, the object that appears larger is perceived as closer than the one that appears smaller.
5. *Height of visual field* - Another cue comes from height in the visual field, more distant objects are usually higher in the visual field than those nearby.
6. *Light and shadow* - Light and shadow contribute to the perception of three dimension and therefore depth (Ramanchandra, 1988).
7. *Motion parallax* - Distance in relative movement provides cues to the difference in distance. Faster relative movement indicates less distance.

2.2.4 Perceptual Illusions

Perceptual illusions are cases in which perception accords neither with how the receptors are stimulated, nor with the characteristics of the objects themselves (Bernstein et al., 1991). They are discrepancies between the appearance of some measurable aspect of the world (such as the size, distance, location, or shape of a visible object) and the corresponding physical measures. For example, in brightness contrast, the appearance of a particular patch is greatly altered by changes in its surroundings. In certain geometrical illusions, the appearance of size or length of horizontal or vertical lines is drastically altered by the addition of a few lines.

Illusions are also possible in the perception of movement, notably in the case of apparent movement that gave birth to the film industry. The film-transport mechanism of a normal professional movie camera is arranged to move the film at the rate of 24 frames per second. The human eye needs 0.25 sec to receive an image and transmit the information to the brain for registration and interpretation. The overlapping of picture information every 1/24 sec easily exceeds the persistence of vision requirements. As a result, the pictures on the screen seem to blend into one, and photographs showing successive positions of a person or object in motion give the illusion of a continuously moving picture.

One of the best known and most studied illusion is the Müller-Lyer illusion, shown in Figure 2.4. Richard Gregory (1968, 1973) has argued that this illusion, represents a misapplication of the depth cues of linear perspective. The divergence of the arrowheads on each side of the shaft on the top makes it seem to appear towards the back, while that of the bottom gives the shaft the appearance of protrusion.

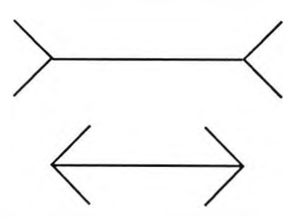


Figure 2.4 Müller-Lyer illusion

The depth cues that underlie the Müller-Lyer illusion is also supported by the fact that increasing the amount of three-dimensional information in an illustration increases the magnitude of the illusion (Leibowitz et al., 1969).

2.3 Recognition

There seems to be two types of processing involved in recognition, top-down processing (Lindsay & Norman, 1977) and the bottom-up processing. In top-down processing, recognition is guided by higher-level cognitive processes and by physiological factors like expectation and motivation (Bernstein et al., 1991). Bottom-up processing, however, begins at the sensory receptors where stimulation is received and it then works its way up to the brain for further analysis. At the brain, feature analysis is performed on the information received and recognition takes place when a match is found and the stimulus is placed into a perceptual category.

Bottom-up processing cannot easily account for the illusion in Figure 2.2, where the stimulus is sometimes assigned to one category and sometimes to another. In a classic experiment (Mayhew, 1992), people were shown a figure similar to the one depicted in Figure 2.5. People who saw a letter first tended to say that the central character was a '**B**', while people who saw the a number first tended to say that it was '**13**'. The shifting perceptions of Figure 2.5 must have something to do with the context in which the stimuli are embedded. The context creates an expectancy about what will be perceived and can therefore bias perception toward one recognition or another. Likewise, motivation has the similar effect of altering perception towards that which we are motivated to.

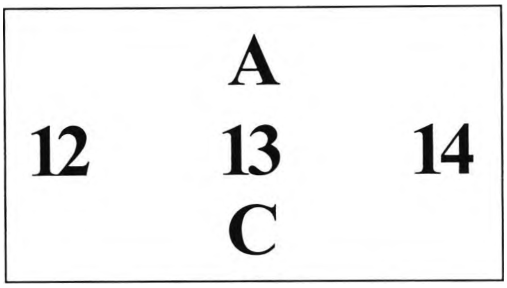


Figure 2.5 Top-down processing

Though the description of both the top-down and bottom-up processes have been given separately, they in fact constantly interact with each other to create a recognizable world. Reading a poorly written or printed passage for example, illustrates the interaction process of the two processes perfectly. When the quality of the raw stimulus on the printed page becomes quite poor, top-down processes compensate to make continued reading possible. Top-down processing in this instance aid us in filling in the gaps where words are not well perceived, thus giving a general idea of the meaning of the text. The reason for this is because the world is redundant in that it gives multiple clues about what is going on. Therefore, even when some information is missing, the concept or meaning can still be grasped through the redundancies provided.

2.4 Attention

Attention is the act of attending, especially through applying the conscious mind and usually by voluntary control, to an object of sense or thought (Bernstein et al., 1991). For example, in order to continue to read this passage, one has to keep ones focus of attention on reading while resisting any other external distractions that might exist. The fact that one must select implies that there are limits to the ability to perceive, think, or do several things at once. Our attention is drawn by external stimuli that are high in intensity, large in size, novelty, contrast, motion, or significance. If, however, the stimulus is repeated or continuous, the response will eventually diminish or disappear altogether. What attracts our attention are any changes in the environment.

While a large amount of sensory information can be absorbed at one time, a selective filter (attention mechanism) reduces the input from one source while that from another source is being analyzed by the brain (Broadbent, 1958). Subsequent experiments, however, showed that the content of an unattended message may be perceived if it is relevant, indicating that some analysis takes place before attention is brought to bear and that motivation, or interest, is important in the activation of attention. As an example, when at a party, a person may be engrossed in a conversation when all of a sudden he hears his name being mentioned in some other conversation all the way across the room. This shows that the sensory system is constantly monitoring the world even if we are not aware of it.

Tasks that initially required full attention may become so automatic that they can later be combined with other activities. For example, most of us are able to listen to the radio or conduct a conversation while driving. However, the difficulty of dividing attention between two tasks increases when the tasks involve the same sensory mechanisms, perhaps because of the anatomical separation of the brain centers controlling the two tasks. In addition, the more difficult the task, the more it interferes with other tasks (Wickens, 1989). Stress during emergency situations tends to narrow attention, and not broaden it (Hockey, 1984).

2.5 Memory

Memory is the process of storing and retrieving information in the brain. It is a key research topic in cognitive science, and psychologists and scientists have proposed many different distinctions between memory and memory processes. There are three well accepted types of memory; episodic, semantic, and procedural (Tulving, 1985). Each of these memory types corresponds to the kind of information it handles. *Episodic memory* includes any memory of a specific event that happened in one's presence - such as what you did over the weekend. *Semantic memory* contains ones factual knowledge that does not involve memory of a specific event. *Procedural memory* involves knowledge of how to do things, such as solving a mathematical problem, assembling a computer, riding a bicycle. Even though the three memories have been categorized separately, they are commonly used together in daily activities. As an example, in driving, episodic memory includes the recollection of the routes taken by the driver, semantic memory include landmarks, and the actual process of driving comes from procedural knowledge.

In order to remember something, we go through three processes. The first stage of the memory process is encoding the information we receive. Information can be encoded by how it sounds (acoustic codes); e.g., when learning a foreign language. It can be encoded as a visual representation (visual code). It can also be encoded by remembering its general meaning (semantic code), e.g., after a speech, we remember the general ideas covered, not the whole speech word for word. The second stage of the memory process is to actually store the information in memory so that it is maintained over a period of time. The final, third stage involves retrieving that stored information when required. Failure to recall, recollect or recognize stems from failure in any one of these three stages of encoding, storing or retrieving.

Three stores of memory have been proposed; sensory, short-term and long-term memory (Atkinson & Shiffrin, 1968), the first two being temporary. Sensory memory or sensory registers store incoming information from the senses for a fraction of a second. This fraction of a second is just long enough to allow processing to occur on the information received so as to turn it into some meaningful pattern (pre-perceptual processes). In all, there are five separate registers for each of the human sensory modalities. If any information in one of these sensory memories are perceived, it gets transferred into short-term memory. In short-term memory, the information undergoes further processing and sometimes with knowledge drawn from long-term memory. If a strong link is made between the processed information and any pre-existing information in long-term memory, the new information would be transferred into the long-term memory.

Sensory registers can receive large amounts of information but can only retain it for no more than one second (Sperling, G., 1960). Because there is so much going on around us, the sensory system cannot keep information around for very long, it has to keep bringing in new information. Short-term memory however, is very limited in its capacity to handle information. Given a list of digits, letters, words, or virtually any type of unit, most of us would only be able to recall about six or seven items from that list. George Miller (1956) wrote a classic paper on short-term memory - "The Magical Number Seven, Plus or Minus Two...". In his paper, short-term memory is limited to seven plus or minus two chunks of information. Chunks being any meaningful grouping of information, not necessarily applying only to discrete elements. Remembering telephone numbers demonstrates this very well. For example, an unordered telephone number say 0734271592 will be difficult to assimilate and remembered, but break them into smaller units and memorization becomes much easier, for example, 073-427 1592. The effect is that the reader does not have to remember ten separate digits but a chunk of three.

The cause of forgetting information in short-term memory can be of either two processes, decay or interference. Two-third of the information in short-term memory is loss within the first eight seconds of perceiving it, and complete dissipation occurs after about twenty seconds (Peterson & Peterson, 1959). Any information in short-term memory will not remain unless it is rehearsed or combined with that in long-term memory. Interference is due to the fact that short-term memory has a capacity limit and any additional information on this limit will only displace what is held. The effectiveness of short-term memory is also based on the information held as very similar items in a list are less likely to be remembered than dissimilar items (Wickens, 1972).

Long-term memory is where information is stored indefinitely. It has a near infinite store as no one has been able to put an upper limit on its capacity. There are two ways information can be transferred from the short-term memory into long-term memory; rehearsal of information or the use semantic codes. Though the use of rehearsal can transfer information into long-term memory, it is not as effective as the use of semantic coding, where information is coded in terms of general meanings or ideas rather than the specifics. Although, long-term memory normally involves semantic codes, it does commonly use visual codes as a means as storing information too. In fact, visual coding has been shown to be very effective in recognition, with greater than 90 percent accuracy in a picture test of 2,500 pictures carried out by Standing, Conezio & Haber (1970). A later test of recognition memory for 10,000 pictures achieved the same level of accuracy (L. Standing, 1973).

Extensive studies have been conducted on forgetting over time. One of greatest the classic is by a German psychologist, Hermann Ebbinghaus (1885) whose studies were based on himself and memory uncontaminated by emotion and pre-existing associations. He found most forgetting occurred in the first nine hours after learning, with very rapid forgetting occurring in the first hour. Additionally, retention decays by as much as 40% in the first 20 minutes and to almost two thirds in ninety. Similar forgetting curves have been show by other researchers after Ebbinghaus, even on information with emotion or pre-existing associations (Bernstein et al., 1991).

Improvement in the amount of material retained, however, can be achieved by practicing active recall during learning, by periodic reviews of the material, and by constantly using the learned material. Techniques like mnemonics can also be used to improve memory. These techniques usually involve the use of associations and various techniques to remember particular facts. Memory techniques used by memory masters such as the 'hooks' and 'link listing' techniques are two such examples. The secret behind good memory for anything is a very strong association of what is permanently known in memory and any new items to be remembered.

There are four traditional explanations why memory fails (Baddeley, 1994). One is that memory traces fade naturally over time as a result of organic processes occurring in the nervous system, although little evidence for this notion exists. A second is that memories become systematically distorted or modified over time. A third is that new learning often interferes with or replaces old learning, a phenomenon known as retroactive inhibition. Finally, some forgetting may be motivated by the needs and wishes of the individual, as in repression.

2.6 People and Computers

Since there is a limitation to the amount of information short-term memory can handle and long-term memory retrieval is a major problem for users, computer interfaces should be sensitive to these weaknesses and offer support wherever they can. Table 2.1, from D. Mayhew (1992) provides a good summary of the strengths and weaknesses of humans and computers. Software designers should know these strengths and weaknesses in order that they may tailor the software to their users' needs. For example, short-term memory is limited to seven plus or minus two chunks of information, therefore computer interfaces should always try to reduce memory load where possible. Designers of systems should never expect users to have to remember and repeat what the computer could be doing for them. If information needs to be held in short-term memory, it should be remembered that this is only possible for about 20 seconds.

Table 2.1 Human and Computer Strengths and Weaknesses (Mayhew, 1992)

	Strengths	Weaknesses
Humans	Selective attention Pattern Recognition Capacity to learn Near-infinite capacity of LTM Rich, multi-keyed LTM	Low-capacity STM Fast decaying STM Slow processing Error prone Unreliable access to LTM
Computers	High-capacity memory Permanent storage Fast processing Error-free processing Reliable memory ccess	Simple template matching Limited learning capacity Limited capacity LTM Limited data integration

The implications for these comparisons for HMI design is that the best role for humans is to monitor, control, be the decision maker, and respond to unexpected events. The computer on the other hand, is better suited to storing and recalling data, processing information in a specified manner, and presenting options and supporting data to the user. Human memory is flexible, but slow, unreliable and imprecise. Computer memory is fast, reliable, and error free, but is limited to what has been programmed.

The more that needs to be held in working memory, the greater the complexity of the task becomes. The limitations of short-term memory hence, produces a powerful desire to complete a task to reduce memory load (commonly known as 'closure'). Closure is the psychological impact of the completion of a task so that it no longer occupies short-term memory. For example, when novices begin to know the importance of saving the file they are working on, say on a word-processor, they keep doing so after each completion of a thought process on document. Each save produces a great sense of relief on the part of the user.

It is natural for novices to have the fear of deleting files or damaging the computer they use. This anxiety may cause the reduction of short-term memory capacity and hence inhibit performance. Designers of systems for novices should make every attempt at putting the user at ease. For example, system designers could include an 'undo' feature in their programs. The undo feature in most programs today provides users with confidence that any error in their part could be rectified easily.

In terms of long-term memory, user interfaces should provide good visual cues as the human ability to recognize is far more efficient than to recall. The strengths of computers, especially their ability for fast, reliable and error free processing should be brought to bear upon the user. This point is discussed further in the Chapter on Icons.

2.7 Control

Another driving force in human life is the necessity to be in control. Some individuals have powerful needs to stay in control of their whole environment, while others are more accepting of their fate. With respect to computers, novices would initially prefer to be guided by computer's but this preference diminishes as they become more experience. There are many ways of providing for this varied need and Microsoft Word for Windows (WinWord) exemplifies this very well. WinWord provides a 'Wizard' which can be invoked to aid in performing a certain task. Wizard does this by providing a step by step guide to the user. This feature is found to be very useful and helpful to novices coming to grips with the word-processor. WinWord also has features to suit the experienced users, features include the ability to create document templates, the ability to customize menus and to modify toolbars. For the more experience, WinWord provides an in-built Visual Basic language whereby users may add new features to the existing word-processor.

2.8 Conclusion

This chapter has covered a number of very important points, that can be considered fundamental principles in the development of user friendly HMIs. They are summarized as follows:

1. The first principle, is on perceptual organization. There are the two basic perceptual organization, figure ground perception and grouping perception. These form the basis for creating simpler interfaces as they dictate how a user will perceive the organization of interface elements. There are various techniques for making certain elements as figure and others as ground. This thesis will cover them in its various HMI design chapters. The grouping principles in this chapter (Section 2.3.1) however, can and should be used to aid designers in organizing various interface elements.
2. The second principle, is on depth perception. Section 2.3.3 provides a list of depth cues that could be used in interface design, especially useful in developing three dimensional interface elements.
3. The next principle is context. Context is important because it dictates how something is likely to be perceived.
4. The fourth principle is on human attention. Human attention is drawn by external stimuli that are high in intensity, large in size, novelty, contrast, motion or significance. What keeps our attention, however, is changes in an environment. Another point to note about human perception, is its limitation. The more attention that is expected from a user, the more complex the task becomes. The difficulty of dividing attention between two tasks increases when the tasks involve the same sensory mechanism. Hence, designers could complement the visual interface with sound, for example; to reduce the attention load of users.
5. The fifth principle is on human working/ short-term memory. Short-term memory is limited to seven, plus or minus two chuncks of information (Miller, 1956). Beyond this figure, short-term memory can be expected to fail. Hence, it is crucial that this principle be designed into the user interface. Closure, for example, is a common method of how humans relief shot-term memory. Closure can be built into an interface by segmenting various tasks into manageable groups. Another thing to note about human memory, is its excellence at recognizing visual image, with close to 90% accuracy of recognizing 10,000 pictures (Standing, 1973). The use of icons at the interface, for instance, benefits from the ability of human memory in recognizing (see Chapter 6). Recognition, as opposed to recall, reduces short-term memory load.

In brief, computers can be designed to compliment the weaknesses of humans, while the strength of humans can be made to compliment the weaknesses of computers. Table 2.1 provides a summary of human- computer strength and weaknesses.

6. The sixth, last principle is on control. Users, especially experienced users, like being in control. The design of applications, should therefore look beyond creating interfaces for novices. For example, short-cuts and custom features in an application go a long way to cater for the experienced.

3. HMI Models and Design

3.1 Introduction

The previous chapter discussed psychology that is relevant to HMI, and forms the groundwork on which this chapter develops. In this chapter, a user HMI model has been worked out to assist designers in constructing conceptual models based on how users interact with computers. The chapter also investigates the designer's conceptual model and how it relates to the formation of user mental model. Detailed discussion is provided on two main areas of HMI design - metaphoric design and navigational systems design. Finally, general design principles, which the author believes to be essential to effective HMI design, are presented.

3.2 Human-Machine Interaction Model

Human-Machine Interactions can depend heavily on the cognitive processes of people. Cognition is the act or process of knowing, and cognitive processes and their studies can include such activities as attention, perception, creativity, memory, reasoning, judgment, thinking, and speech.

The most important feature of an HMI model is the flow and feedback of information through its interface. To describe the HMI model, let us look at how a user would retrieve an address from a computer database. Let us assume that the user has not used the system software before. The goal of the user is to retrieve an address. With this in mind, the user defines the task and formulates the required action sequence. The user does this by first forming a mental model of the computer system and how he/she will be able to carry out the task. The forming of the mental model could be subconscious. Let us say that the mental model formed is based on the analogy of an "address book", with names and addresses stored in the computer memory in some ordered sequence. Having this mental model in mind, the user turns to the system software. The mental model of the user is re-affirmed by its appearance. The user sees an electronic filofax call the Lotus Organizer (Figure 3.1), on screen. At this point, the user has made an interpretation based on his/her perception of the software. The interpretation (user model) will not always match the system model. The matching of the system model to the user model forms a good mental model. In this case, the perception of a "filofax" would lead most users familiar with a filofax to the interpretation that it would behave and have functionality similar to a real filofax. Hence, the appearance forms a good mental model.

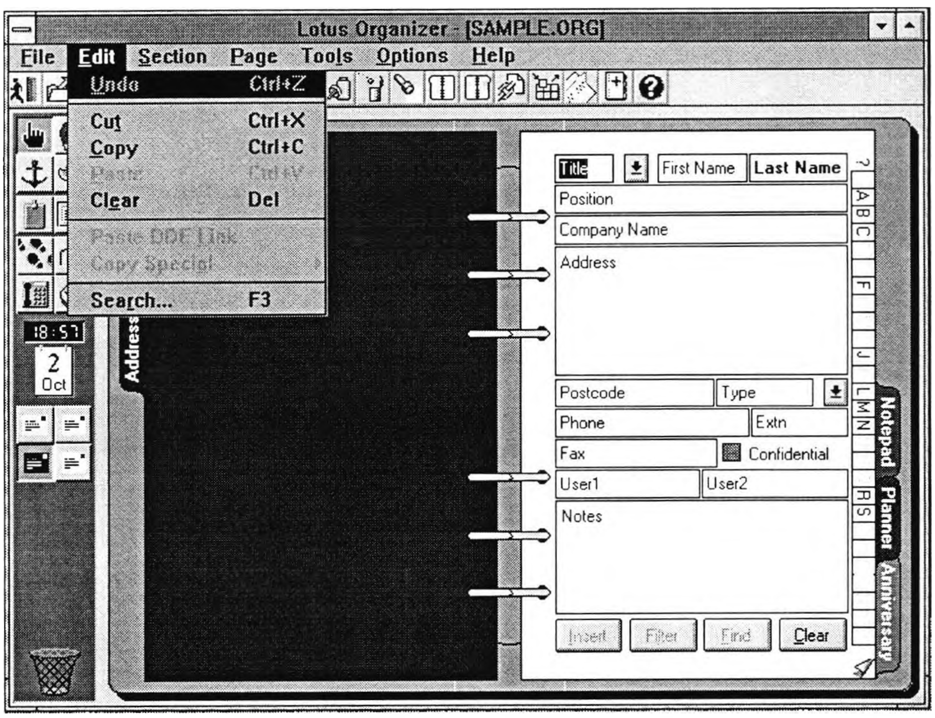


Figure 3.1 Typical Lotus Organizer screen

The user sees the tabs on the electronic filofax appear just like that on a conventional filofax. This only affirms the user's mental model of the system. The system awaits instructions. The user clicks the tab of the electronic filofax which states "Addresses" with the mouse cursor, assuming the user has used a mouse before. The system response by displaying a flip of pages and then displays the first page of the address book. There are alphabetical tabs running along the address book, ranging from A to Z. The system awaits input again.

There are two ways of searching for the appropriate address. The filofax way would be to search through the address book section of the electronic filofax for the appropriate name of the addressee. The quickest way, however, would be to let the computer do the searching. The latter just dawns on the user as the user has past experiences with computers. The user starts to look at the main menu bar at the top of the electronic filofax. It reads File, Edit, Section, Page etc. The user selects the main menu items one at a time starting from the left, looking for some command name like "search..." or "find...". An appropriate command is found and is then executed. The system displays an hour glass in place of the mouse cursor while "churning" away in the background looking for the name in its files. The hour glass acts as a feedback to the user that the system is in progress of carrying out the requested task. The system software finds the address and flips the electronic filofax to the appropriate page, highlighting the search. The user makes an evaluation on the search and notes the address.

A major component of this interaction is the flow of control and information between the user and the computer in carrying out the task. The computer gives information to prompt the user for input, and the user supplies input that directs the subsequent operations. Smooth operation of this system requires error free states on both parts, user and computer. Such errors within the computer are generally well defined and can come from three areas. These displayable errors occur when (1) the input values fall outside the allowable range or disagree with the required type, (2) the call is made to unavailable functions or locations, and (3) the requested resources are not available. In contrast, user errors are not as well defined as the source of errors are subjective in nature. User error states are characterized by confusion, lack of understanding, and lack of knowledge of what to do next.

Figure 3.2, shows a Human-Machine Interaction (HMI) model. The model describes the relationship of the cognitive processes of the human operator and the computing processes required for the task. The interaction of the two is represented by the flow of information and control between them. The first thing to note about the model is that it is embedded into both a task environment and a machine environment. Task environment describes such things as working constraints, time constraints, office layouts, costs of errors, provisions of help and guidance, and so on. The machine environment on the other hand, describes the machine processes which takes place outside the computer. A machine environment includes any external device the computer is controlling or monitoring. This could range from a simple fax/modem to a sophisticated assembly robot used in industry.

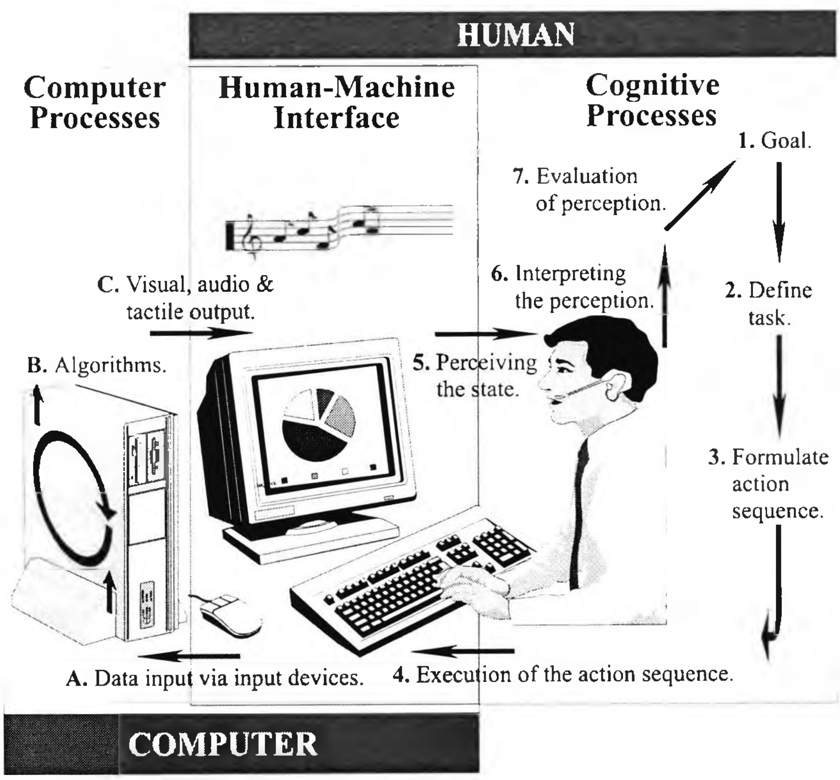


Figure 3.2 Human-Machine Interaction (HMI) model

The non-overlapped area within both squares represent processes involved in tasks that are not directly related to the man/machine interface. The overlapping area (shown shaded), represent processes that pertain to the interface. The interface is an area of connection made between the user and the computer so that they can work with one another. According to IBM's Common User Access (CUA) user interface guidelines (1992), "A user interface is the set of techniques and mechanisms that a person uses to interact with an object. Any kind of object has a user interface, and an object's interface is developed according to a user's needs and reasons for using the object."

The contribution on the overlapped area by the human operator includes necessary motoring skills in using the system hardware and the perception received from the system software at the various stages of the interaction. The contribution made by the computer system on the other hand includes input devices, manuals, visual display, audio and sometimes tactile feedback from the system. The act of interacting with a computer could be viewed very much as an act of communication. The aim being the transfer of 'meaningful' information between the two and the goal is the efficient and effective achievement of user goals.

This act of communication can be seen as taking place at three layers, each layer forming a reliable and transparent medium to the layer above, and providing structured information to the layer below. The actual methods used are not available outside a layer, and no data is shared apart from the data to be communicated. The three layers include the physical, the syntactic, and the semantic.

At some point, the user has to connect physically to the machine for the purpose of exchanging information. This is known as the physical layer and is the domain of the ergonomist. Now that we have a means of communication, the physical layer; we require a way of carrying a more structured information. This layer is known as the syntactic layer and constitutes a formal means of communication, as grammar would to the English Language. Here, the easier it is for the user to learn the 'grammar,' the easier it will be for the user to utilize the application. Finally, the semantic layer gives the user a way of communicating meaning. In the English Language, the phrase "The dog bit Tom." would have an entirely different meaning to the phrase "Tom bit the dog."; especially for Tom. Both sentences however, are syntactically correct, no words were added or deleted but just the way they were arranged made all the difference to its meaning. Likewise, the way one goes about executing a task in a software application could thus make a great difference to the end result.

In performing a task, the human operator is likely to go through seven stages of action in interacting with the computer. An example of this can be seen in an "address retrieval" example. The user starts by having a goal, and that goal is to retrieve an address from a database. The goal however, is vague as it does not state precisely what to do in order to obtain it. This is where the next stage of forming a task definition comes into play. A task definition is a specific action taken to get to the goal. Yet even task definitions are not always specific enough to control actions as they can change with circumstance. In the "address retrieval" example, the user changes his/her mind as to how he/she goes about obtaining the address. The goal has not changed but the means has.

In the example, the "filofax" metaphor gives the user a guide as to how he/she should go about in executing a task within that environment. The use of metaphors in HMI will be discussed further in Section 3.5.1. For now, a metaphor aids in forming a constructive mental model in using an application. During the interaction with the computer, the user would evaluate the actions made and compare them with the desired outcome. The various strategies of the user are triggered into operation by the detection of a mismatch between the state of the system and the user's internal model of the system. The detection of a mismatch can be broken down to three action stages: first the act of perceiving what has happened; second, trying to make sense of it (interpreting it); and finally, comparing what has happened with what was wanted.

In the example, the task was simple and the seven stages of action can be clearly defined. However, in the real world, tasks are normally more complex. A goal has to be subdivided into subgoals in order that they may be met and ultimately the achievement of the main goal. The problem is, often when people dwell in subgoals for too long, they tend to forget the main goal. Along the way, people sometimes change goals or discard them all together. Sometimes goals are not clearly defined, people think of what they don't want rather than what they do want. Even if there is a well defined goal, people sometimes lack concrete plans to carrying them out.

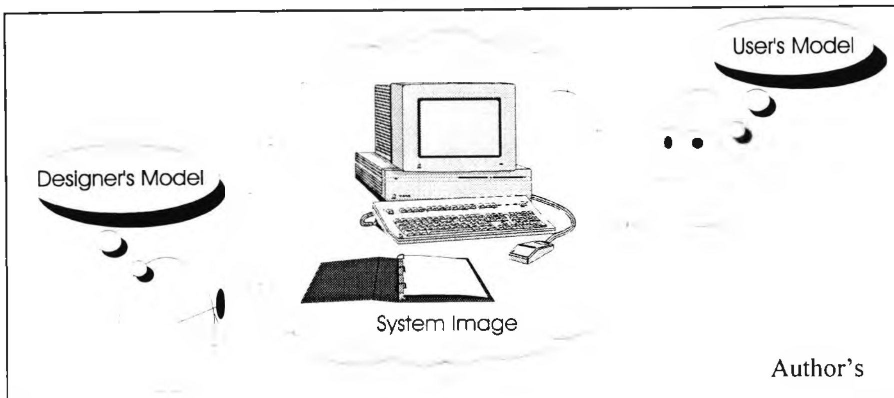
A particular thing to note about this model is that people do not always behave in a rational way. People do not always start with high-level goals and then work to achieve them. Often goals are obscure, and plans are ill-defined. Therefore, these factors have to be taken account when using this model to represent the interaction between human and machine. Designers of Human-Machine Interfaces should bear in mind that "users are unpredictable" and that we can only adapt the user interface to the people who would use them by actually testing it on them.

Alongside this human operation, the computer has its own internal processes to carry out. The action sequence would ideally follow the order shown by the arrows in Figure 3.2. Starting with the initial goal formulation by the user, the user would then go through the next two action stages (stages 2 & 3) and then start to interface with the computer at stage 4. Next, the computer would go through its stages of recognizing the user commands at A, executing the commands at B, and finally, returning the result of the execution through the various communication media shown at C. The user then evaluates the response of the computer with that of his/her goal and if need be the whole cycle would begin again.

3.3 Mental Model

Mental models of a system are structures and processes which are either provided by an instructor or formed through user experience with such systems. Mental models, whether accurate or not, will account for user's behavior and experience with a system. As suggested by various researchers (Craik, 1943; Norman, 1986; Carroll et al., 1983, 1984; Gentner, 1983), users translate interactions with external events into internal models which emphasize the structural aspects of the model. This action of constructing an internal model from external events help users predict outcomes of interaction, and it serves as a framework for understanding, analysis and decision making.

Norman (1983a) has elaborated further on the role of mental models in the design and usage of interactive systems, as seen in Figure 3.3. According to Norman, the conceptual model is the model held by the designer or instructor of the system. This is equivalent to the designer's model shown in the illustration of Figure 3.3. The system image is what the system portrays to the user, and consists of various types of input/ output devices and manuals or any other form of system instruction. The mental model or user's model is the model extracted or created by the user from his/ her interaction with the system. This model, however, may not necessarily correspond to the conceptual model of the system designer. The aim of the HMI designer should be to produce as best as possible, a system image that accurately reflects the nature, potential and working of the system. When the system image accurately reflects the designer's model, and if the designer's model is based on the user's model, an effective and easy to use HMI is produced.



Norman's		
Conceptual Model	System Image	Mental Model

Figure 3.3 Summary of Norman's model of the design and usage of interactive systems

Studies indicate that user performance improves when they are given a conceptual model of the computer system they are using. (Borgman, 1984; Halasz, 1984; Mayer, 1981; Moran, 1981). Studies also indicate that users are more readily incorporate given models then they induce new ones (Moran, 1981; Norman, 1986). Overall, mental models have been shown to improve accuracy (Larkin, 1983; Staggers & Norcio, 1993), efficiency and problem solving skills (Halasz,1984; Staggers & Norcio, 1993).

3.4 Conceptual Model

The designer's conceptual model describes three things; the *objects* the user works with, their *presentation* to the user, and the *interaction* techniques used to manipulate the user's objects. These are commonly illustrated in an 'iceberg' chart as in Figure 3.4 (IBM CUA Guidelines, 1992).

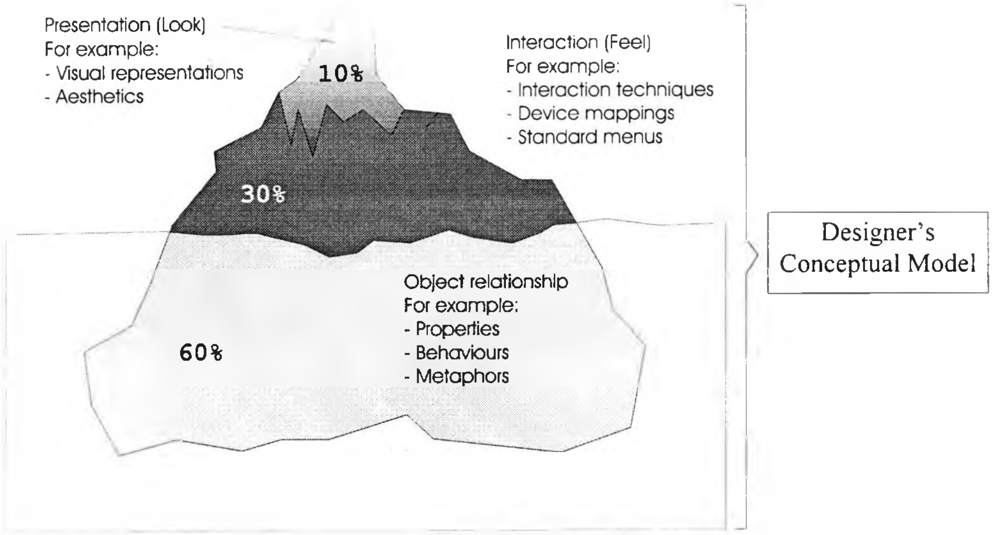


Figure 3.4 The Iceberg Chart

When using a software for the very first time, the first thing the user experiences is the look or the presentation of the application. When the user begins to use the product, he or she gets a feel of the interaction techniques employed. As the user becomes more experienced, the novelty of the look and feel of the product wear off. At this stage, if the application does not support the objects and information intuitively, the user's so called 'feel good' factor of the application disappears. Additionally, if the application does not match the user's model of the system and any metaphors the user might have of the application, the positive feelings of the user will not be maintained. This can eventually lead to the user's disinterest and abandonment of the application.

This model fits the iceberg metaphor very well. The tip of the iceberg represents the "look" of an application and constitutes about 10% of the substance of the designer's model. The "look" of an application includes the use of text, graphic, animation, colour, sound and screen layout. Even though this part of the iceberg is good for catching potential users and keeping their visual interest, it is, after all, only cosmetic. The second part of the iceberg dictates the "feel" of an application and accounts for about 30% of the designer's model. It defines the interactive methods of an application and includes the use of a keyboard, function keys, mouse, joystick, microphone, virtual reality equipment such as data gloves and virtual reality goggles (for examples, see Chapter 4). This part of the iceberg also determines the style of the application; whether it be command line, menus, natural language, direct manipulation, virtual reality or agent based. The style of an application is closely coupled with interaction devices employed (Chapter 4).

By far the most important part of the designer's model is the submerged part of the iceberg, which commands 60% of the designer's model. This part is made up of properties of objects contained within an application and the relationships these objects hold with each other and eventually the HMI. The properties of an object dictates how an object behaves with other objects while also determining its own behavior when manipulated upon directly. For example, when a user points and clicks the mouse pointer on a 3-Dimensional representation of a button on screen, the user might come to expect a few reactions. One, to see the button being depressed and for it to stay down if it is a toggle switch. Two, the user might expect an audio response, as in a real switch. Three, for the application to carry out an action if the button is an action key and not just a toggle switch. Likewise, when a user mouse clicks on a down arrow key of a scroll bar, the application response should be to scroll down the manipulated object and not to scroll it up or sideways.

Object relationships also governs how an application is structured and it provides users with a framework of how an application is organized. Natural and intuitive organization of data and processes is achieved through performing such activities as task analysis, implementation and ongoing testing on an iterative cycle. By carrying out task analysis and testing on prospective users, designers are better able to infer methods to use within a system.

The reason this part of the iceberg holds 60% substance of the designer's overall model is clearly seen in today's operating system environments (e.g.'s Microsoft's Windows, IBM's OS/2 and Macintosh's Mac OS). All applications written for these environments have very similar look and feel to them, as they all apply the same standard user interface, input devices and follow the same guidelines. In spite of this, the ease of use of say one Windows application compared with another can very dramatically. These differences can be attributed to this part of the iceberg. This part of the iceberg is submerged and appropriately so, as a lot of programmers and designers today are not directly aware of this part of the designer's model and mainly concern themselves with the "look" and "feel" of an application.

The synergy of these three parts of the iceberg (object relationship, feel and look) should makeup what is known as the conceptual model of the designer (see Figure 3.4). If this is reflected well in the system image then the mental model formed by users will be built from the conceptual model of the designer. And, if the conceptual model is built from an accurate model of users, the HMI should prove intuitive to most users.

The rest of this chapter will concentrate on object relationships, as the look and feel aspects of application design are in themselves too large to be discussed in length in this chapter. These, however, are covered in detail in Chapters 4 through 7.

3.5 Representing Object Relationships

As stated in Section 3.3, object relationship is by far the most important part of the designer's conceptual model. However, creating an application with a well planned object relationship does not necessarily make it 60% user friendly. It is not the individual parts of the iceberg (look, feel or object relationship) that make up the ease of use, but the sum of the whole. Currently, the two most effective means of representing object relationships is through the use of metaphors and or a navigational system.

The organization of any application is very individualistic as it is very much dependent on task requirements. Organizing processes and data within an application has a lot to do with prioritizing and finding the right links or relationships. A natural and intuitive organization of structures, constituting data and processes is achieved through performing such activities as task analysis, implementation and ongoing testing on the task to be computerized. The whole process is usually iterative in nature. By carrying out task analysis and testing on users, designers should be able to infer appropriate metaphors and/ or navigational system to use in achieving an effective method of presenting object relationship within an application. These representations should also be made to reflect on the other two tiers (look and feel) of the iceberg chart.

Metaphors tend to dictate more on the functionality of an application, and a navigational system the organization of data or information. A completely functional application, like the simple Notepad for Windows, consists of a single metaphor; "a notepad," and without the requirement of a navigational system. Microsoft Encarta, with its vast encyclopedic database on the other hand, constitutes more of a navigational system then a metaphoric one. A combination of the two would probably be found in an application with both plenty of functionality and information, as in a database.

3.5.1 Metaphors

Metaphors are part of our daily lives and to the extent that we may not realize we are using them at times. For example, such commonly heard expressions as "let's look at the problem from a different angle", "let's shed some light on the problem" and "let's examine the problem from a different perspective" are based on the metaphor that problems are seen as visible objects (Lakoff and Johnson, 1980). Likewise, when we are trying to describe something new to someone, we often employ analogies or metaphors to assist the listener in understanding our description. For example, we might say that using a word processor on a computer is likened to using a type writer and then go on to describe their similarities and then their dissimilarities.

We use metaphors in our daily communication and using them in computer applications to communicate functionality is similarly meaningful. The concept of borrowing techniques from other domains in creating interface metaphors that anchor user's understanding of the computer to something with which they are already familiar is known as an interface metaphor. This approach seeks to increase the initial familiarity of action, procedures and concepts which make learning and remembering an application very much easier. Like mental models, metaphors are generated and used by users in their interaction with computers, even if they are not given one at the onset (Mack, Lewis & Carroll, 1983; Carroll, Mack & Kellogg, 1988).

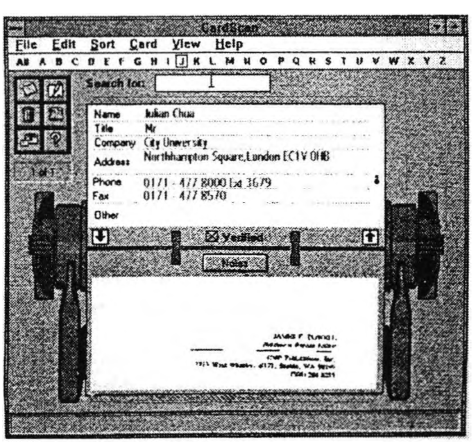
The Apple Operating System (OS) is known to be one of the easiest OS's to use. It employs an office desktop metaphor in representing various elements of it's OS as documents, folders, filing cabinet, mail trays, waste paper basket etc. The underlying processes behave in many similar ways to the manual processes that this metaphor substantially reinforces the usability of the system. Users are able to determine the attributes of the system's objects by associating their iconic representation with familiar physical objects and their attributes. Today, similar desktop metaphors are found across the spectrum of graphical operating systems, a testament to the effectiveness of the office desktop metaphor in achieving widespread acceptance among users because of its ease of use. The spreadsheet is another very successful example of employing metaphors in computer applications. Spreadsheets typically employ a ledger sheet metaphor to hold data in a matrix-structure similar to those found in a ledger sheet. Table 3.1 lists some additional examples of commercial applications that employ interface metaphors.

Table 3.1 Commercial applications with their associated metaphors

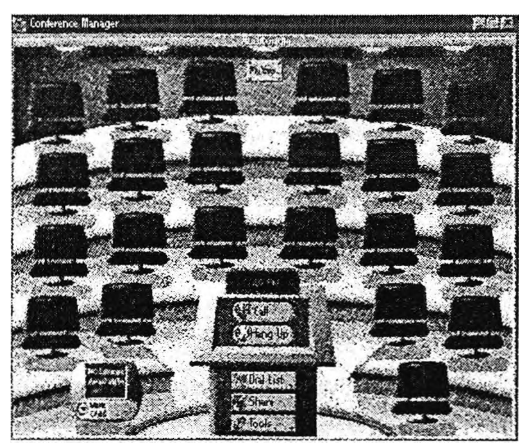
Application Area	Commercial Examples	Metaphor	Based Analogy
Operating Systems	System 7.5, Windows 3.1/ NT/ 95, OS/2, NextStep	Office Desktop	Office tasks and organization
Spreadsheets	Lotus 1-2-3, VisiCalc, Excel	Ledger Sheet	Data tables
Information Managers	Organizer, TaskTimer, Schedule+, SideKick	FiloFax	Diary, contact information, notepad, calculator, project manager
Hypertext	Help Files, Multimedia Information Databases	Notecards	Flexible organization of structured text
Object Oriented Programming Languages	SmallTalk C++, Delphi, Java	Theater Physical World	Physical objects, their functions and properties
Iconic/ Graphical Languages	LabView, LabTech Notebook, Authorware, Icon Author	Flow Diagram, Pipeline Network, Circuit Diagram	Flowcharts, pipeline or electrical circuits

Metaphors employed by some applications are not immediately apparent as they sometimes are abstract and not represented directly in the HMI. For example, the notecards metaphor (Table 3.1) employed by hypertext applications are not always obvious unless a visual representation of notecards are provided. Object oriented programming languages are another example where the theater metaphor of the SmallTalk programming language, or the physical world metaphor of the other programming languages mentioned in Table 3.1 are not obvious. In such circumstances, users are best informed about the metaphors employed through product literature. Once understood, the concept often becomes apparent to users.

In other cases however, the metaphor employed is immediately apparent at the interface. The reader is invited to take a look at the HMIs of Figure 3.5, and guess the metaphor employed by each. The first application is called CardScan and is used for storing and managing contacts. It employs a rolodex metaphor. The second application is call ProShare 200 and is used for multi-user video conferencing. It employs an auditorium conferencing room metaphor. The third application is a personal information manager (PIM) for the home. It employs a home suite metaphor that is more apparent and life-like than the Macintosh or PC desktop counterparts. These approaches to representing a metaphor in the interface seek to further increase the initial familiarity of action, procedures and concepts of applications.

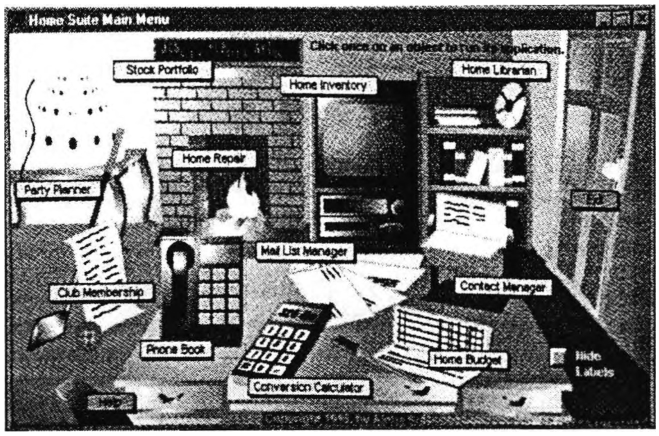


(a) CardScan by Corex Technologies Corp.



(b) ProShare 200 by Intel

Figure 3.5 Metaphors used by some diverse commercial applications (continue...)



(c) Complete Home Suite by Alpha Software Corp.

Figure 3.5 Metaphors used by some diverse commercial applications

In many cases, metaphors have been found to improve learning, but there are reported cases where mismatches between a metaphor and its target domain are sometimes the cause of problems (Douglas & Moran, 1983; Mack, Lewis & Carroll, 1983). Taking the type writer metaphor, for example, the backspace key on a typewriter allows users to go back to certain characters for correction, whereas this same key on a computer deletes any character to the left of it. This difference, though small, does cause problems to initial users familiar to a type writer.

Another danger of metaphors is that it usually represent both an abstract and simplification of the underlying facilities of an application that can become a constraining factor to users. For example, users that are comfortable with the similarities between a word processor and their old type writer might not see too far beyond the features that a type writer might bring them when using a word processor. If so, they might lose out on the benefits that a word processor provides.

No matter how well-designed an interface metaphor may be, inaccurate mappings to the target domain will inevitably exist. However, these differences are often necessary, otherwise why use a word processor when a user can use a type writer, for example. To warrant the use of a word processor, it must have added features that users want. As such, word processors do have the extra benefits of being able to go back and edit a document, call up an in-built thesaurus, spell and grammar check a document, perform desktop publishing features etc.

When applications become large and complex, a single metaphor is often unable to meet the challenge of continuous communication a metaphor brings. In this circumstance, composite metaphors are commonly employed. For example, word processors often use a clipboard metaphor to describe its cut (or copy) and paste features. When a user highlights a word, sentence or graphic and selects the scissor icon in the toolbar of its word processor, the user moved the selected item into a clipboard. The clipboard acts as a metaphor where, in reality, the selected item was moved into part of the system memory. Now, if the user selects the clipboard icon on the toolbar, the item in the clipboard is pasted back into the current position of the text cursor. As such, composite metaphors are frequently used to address the problem of mismatches in metaphors. However, metaphor mismatches should not always be seen as being negative as they do provide users with the opportunity of seeing a target domain in a new light (Tourangaeu & Sternberg, 1882). Metaphor mismatches can act as a stimulant to exploration that encourages users to learn more about an application. When users become stuck with a metaphor mismatch, they will often look for other means of achieving their objective, and this leads to further exploration.

3.5.1.1 Generating and Identifying Appropriate Metaphors

Every application design process should begin at the bottom of the iceberg chart of Figure 3.4. This is where objects and methods of an application are defined and structured. Once this is achieved, the visual and aesthetic aspects of the interface, such as icons, will usually evolve logically and easily. The generation of metaphors themselves can come from three different sources; predecessor tools and systems, human propensities and creative instinct (Carroll et al., 1988). Metaphors are commonly generated in what is known as a brainstorming session where ideas based on application requirements are allowed to flow uninterrupted.

The most obvious choice for a metaphor is the actual physical tool used in performing such a task. Studying people as they perform their equivalent manual tasks can provide valuable insights about ways to represent them on computer. In such circumstances, the metaphor generated is usually formed from superficial similarities (Gick & Holyoak, 1983). For example, in the word processing example of Section 3.5, the cut action was represented by a pair of scissors. In an office environment, where word processors are commonly used, and even at home, a pair of scissors would probably be the best candidate for such an action. Other tools used in cutting are also generated at this stage, but the final chosen tool will be based on the required context. For example, if it was a surgical application however, the best tool for that purpose would probably be a surgical blade and not a pair of scissors.

Metaphors based on human propensities, are based on human cognition, perception and motivational strength and weaknesses. For example, direct manipulation interfaces with its simulation of familiar real world actions (pointing, dragging and grasping) and appearances (physical desktops, folders, trash can, etc.) facilitate the human learning process. When there exist no previous predecessor tools or systems however, metaphors generated have to come from creative instinct. For example, Macromedia Director, an industry standard for creating and distributing multimedia interactive applications, employs a creative theater metaphor; complete with a stage, cast and score. Even the product name "Director" reinforces the theatre metaphor where the designer becomes the director of a "play" or "movie" (Director movie). Elements to be included in a multimedia application are known as cast members. A movie is created by assigning cast members to various parts of a score. The score tells Director what the cast members should do on a frame by frame basis, very much like a "script", and all actions are performed on a Director's "stage."

Mountford (1990) has identified various techniques of generating metaphors, they are here summarized:-

1. Look for new uses of existing Objects, e.g., the current "desktop"
2. Adapt Objects to something else, e.g., make the "desktop" a "kitchen top"

3. Modify Objects for a new purpose, e.g., use sound to provide information about adjacent activities
4. Add new features to existing Objects, e.g., add drawers to the "desktop"
5. Subtract from existing objects, e.g., remove objects until we are down to basic elements of a task
6. Rearrange elements in an Object, e.g., reorganize the "desktop"
7. Reverse or transpose Objects, e.g., Turn metaphors inside out to create interesting ideas
8. Create a hierarchy or families of Objects, e.g., waste paper basket, filing cabinets, folders and documents are elements of an office desktop metaphor. Folders and documents are in themselves components of the filing cabinet metaphor etc.

In order for a metaphor to be effective, it should have a good amount of applicable structure. The structure should also be extensible and be easily representable at the interface. The desktop metaphor is a good example of a rich structure. It provides designers with a large number of possibilities in terms of functional and visual representability. Additionally, the metaphor with the most matches and least problematic mismatches is probably the best candidate for an application. Problematic mismatches are often caused by direct differences between a metaphor and the target domain, as in the backspace example given earlier. Mismatches due to representations outside the structure of a metaphor do not pose a serious problem as they can often be met by composite or complementary metaphors. The difficulty designers have is to make it obvious to users when a metaphor ends and when a new one begins. When such boundaries are clearly defined, users will know when to look for alternative means of doing things.

3.5.1.2 Managing Metaphor Mismatches

As mentioned in the Section 3.5, where there is a metaphor, there will exist mismatches to it. The key to managing these mismatches is to provide users with knowledge of where and when a metaphor breaks down, and sometimes where and when another takes it's place. The best method of achieving this is through user exploration of the application itself. A well designed visual interface will often entice users to explore an application. Visibility of items on a user interfaces, like three dimensional push buttons, suggest, reminds and invite, the exploration of new ideas and methods. To encourage exploration, users must also be able to explore with confidence and without fear that any of their actions could result in harm towards the computer or it's data. One of the best features most found in applications today, that promotes some degree of confidence in users to explore, is the "Undo" function. The undo function provide users with the assurance that any undesirable effects may be undone easily, hence increasing their confidence towards exploration of the application.

Another method of encouraging exploration in users is through progressive disclosure of functionality. For example, all applications in Microsoft Office 95 have a "Tip Wizard" which introduces users to a new function at each new working session or at any time during the working session. This provides users with an opportunity to learn something new about the application. Microsoft Office 95 applications also have an "Answer Wizard", which provides answers to questions entered in plain English, such as: "How do I create a table?" The response to a question in Answer Wizard is a step-by-step instruction on how to achieve the intended task. Other help features include pop-up cue words that describes the function of each iconic toolbar button in a word or two when the mouse cursor is placed over them. At the same time, a brief functional description is also provided in a status bar, describing further its functionality. Another technique of achieving progressive disclosure is by placing common or frequently used functions in toolbars where they are easier to access; while advanced commands are put in pull down menus.

The undo method and the progressive disclosure techniques discussed thus far, are currently in use by some commercial applications. However, the author observes that current applications still lack interface techniques that cater for users as they progress from being a novice to advanced user. Presently, advance users have the option of using short-cut key strokes, customized user interfaces and even programmable extensions to further adapt an application to their requirement. The transition from being a novice to an advance user however, is not reflected at the interface. The author therefore, proposes an interface technique that gradually transforms with the expertise level of a user. The author uses the term for this type of interface as "User Adaptable Interfaces" (UAI).

The idea of an UAI can be explained by considering the current pull-down menu and toolbar interfaces. When a user starts an application for the very first time, the menu and toolbar display only the most common functions a novice is likely to use. This is a minimalist approach, as users do not concern themselves with more advance functions until the appropriate time. With minimum functions being displayed, screen clutter is also reduced. This approach should enable novice users to better master the functions provided without being confused. When users are ready, they can choose to move on to the next level, where more functionality is displayed. This way, menus and toolbars can be customized for different levels of users; beginners, intermediate and advance users. As the interface adapts to users, users become more comfortable in exploring an application.

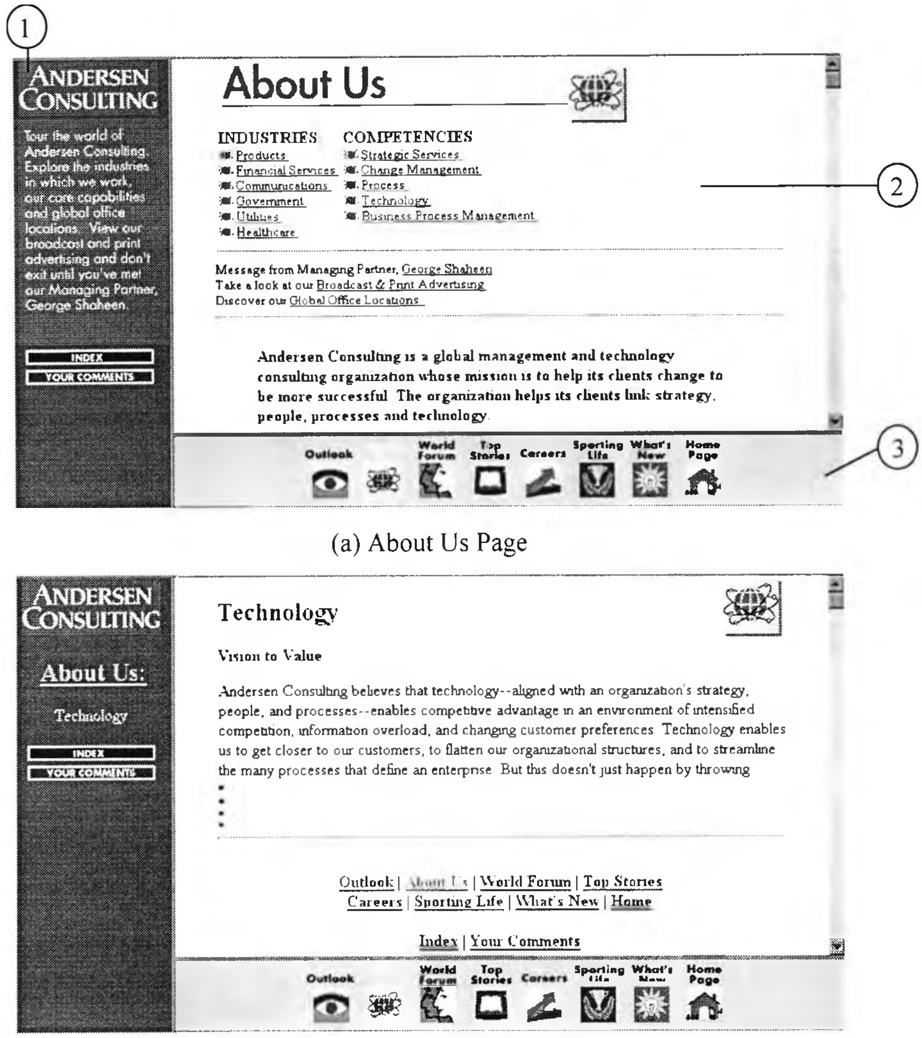
3.5.1.3 User Testing

As with any design process, user testing is crucial to the usability and user friendliness of an application. Likewise, metaphor design is no exception. No matter how well a metaphor fits the structure and functionality of an application, if users cannot see the connection between it and the functions it is trying to relate, the metaphor fails.

3.5.2 Navigational Systems

When there are two or more screens of information that users need to move between, some form of navigational system is required. Generally, such an application constitutes a database system where users have to navigate to attain specific or further information. The information content itself can be narrow, such as information on covermeters, or wide, such as a broad coverage of non-destructive testing (NDT) equipment used in the construction industry. The purpose of this section is to define and discuss the attributes that makeup a good navigational system; one that users will find intuitive and friendly.

The author finds that three attributes are prevalent in applications which possess an effective navigational system. They are an intuitive application structure, a clear and consistent navigational system and an informed user location within the information space or structure. With respect to the latter, users should always know where they are, where they have been and where they can go. The Andersen Consulting World Wide Web (WWW) site provides a good case study in that it encompasses all three attributes. Figure 3.6(a) shows the “About Us” page of Andersen Consulting. The page itself can be divided into three rectangular areas. On the far left, is an area stretching the whole height of the page (Area 1); at top right, a scrollable area (Area 2) and at the bottom right, an area filled with icons (Area 3). Area 1 displays in large print, the name of the company. This constantly reminds visitors that they are currently viewing the Andersen Consulting WWW site. Below it is a brief description about the company itself. Area 2 talks about the industries Andersen Consulting is involved with and it’s five competency groups, all of which provide links to further descriptions, commonly known as hypertext links. Again the area is clearly marked with a large “About Us” text sign along with its representable icon to the right of the it. These features provide users with a sense of where they are which is also reinforced in Area 3 where the “About Us” text and icon is grayed out, indicating the selected topic. Area 3 allows readers to jump from one topic page to another with a single mouse click on any of the displayed icons. This feature provides readers with information of where they can go from the current topic page. Note, another good feature that almost all navigable systems provide is the ability to jump back to the home or main page, see the last icon on the right of Area 3. In other applications, this can be seen as a main menu.



(a) About Us Page

(b) Technology Page

Figure 3.6 Andersen Consulting WWW site

Figure 3.6(b) depicts a screen display of when a reader selects the hypertext word "Technology" in the competencies group of Figure 3.6(a). In Area 1 of Figure 3.6(b), a hierarchical trail is provided to inform the reader of his/ her current position within the information hierarchy. The current position is also reflected in Area 2 with the appropriate "Technology" heading. Following on the tradition of web pages, the bottom section of Area 2 provides hypertext links to the same topics covered in Area 3. Here, however, any topics that have been visited will be shown in gray, reminding readers that they have seen or visited these topics. Again, the About Us topic is grayed out in Area 3 as the reader is currently in that topic.

The icons of Area 3 and their equivalent hypertext links in Area 2 are the navigational controls of the site. Note their consistency when navigating from one topic area to another. An intuitive site structure is not demonstrable here as this often comes with interacting with the application itself. This attribute has a lot to do with having an effective structure to begin with, but also to have this blend well with the navigational controls and locational feedback of users within the system. An intuitively structured site provides users with a strong mental representation of the structure of the site, even when this is not directly represented visually on screen.

The Internet and Intranet has gained so much popularity in recent years that Bill Gates of Microsoft is integrating the Web-style navigational system (Web browser) into it's next to be released Windows 95 upgrade, codename Nashville (MacUser, July 1996). The Web metaphor of Nashville will provide a seamless integration of computer systems and the Web. Even the next to be released Microsoft Office 97 will support built-in hyperlinking, searching and Web-style navigation. More and more applications in the future will incorporate this seamless integration with the Web, calling for more applications to be built with a Web-style navigational system.

Practically all multimedia based titles also incorporate a navigational system of sorts. Figure 3.7(a) depicts the main screen of a Macromedia Multimedia Showcase. In the center of the screen are seven items that makeup the main menu of the application. To the far right of the center are three additional menu items where users may request for help, make preferences or exit the showcase. Below the main screen are some navigational controls, also shown inverted and enlarged for clarity. These control buttons act in the same way as video recorder controls and are here used to control the multimedia presentation. To the right of these controls are the words "Main Menu", which is a menu bar depicting the same menu options as on the main screen when selected. The "Main Menu" also acts as an anchor by providing users with a trail of where they are in the screen hierarchy, see Figure 3.7(b). To ease the descriptions to come, the author will refer to this area as the navigation bar.

Figure 3.7(b) depicts the Tools screen, users get to it by selecting the Tools menu option on the main menu. Note how the navigation bar leaves a trail of the current screen position with respect to the Main Menu screen. The screen is reinforced with a picture of a hammer to represent that users are in the Tools screen. By selecting the Authorware menu item on the right of the hammer, users are transported to another screen, see Figure 3.7(c). Note again, the trail provided in the navigation bar and its consistency with the other screens. The other two items to the right of the navigation bar are two screen linkable items that users can jump to with a single mouse click. They are labeled as "Authorware Interactive Studio" and "Royalty-free Licensing" respectively. In the Showcase, the intuitiveness of the site structure is amplified by having a visual hierarchical representational trail of selected topics.

(a) Main Menu Screen

Figure 3.7 Macromedia Showcase (continue …)

(b) Tools Screen

(c) Authorware Screen

Figure 3.7 Macromedia Showcase

Figure 3.8 depicts some of the paths that can be taken in the Macromedia Showcase, by using a flowchart. Coverage of the flowchart follows on the three screens depicted in Figure 3.7. In designing navigational systems, a flow chart forms the basis of developing intuitive application structure design. It is very important to get this stage right and the only way of achieving this is through user testing of the structure. In the case of multimedia based applications, a storyboard as used in movie making or TV commercials is commonly used. Storyboards provide a convenient means to communicate development ideas to an entire in house team and prospective audiences. Storyboards frequently show the function and approximate layout of all the graphic components and are more detailed version of flowcharts. Flowchart design is the macro model of object relationship design, whereas storyboards incorporate the look and feel of application design to flowchart design.

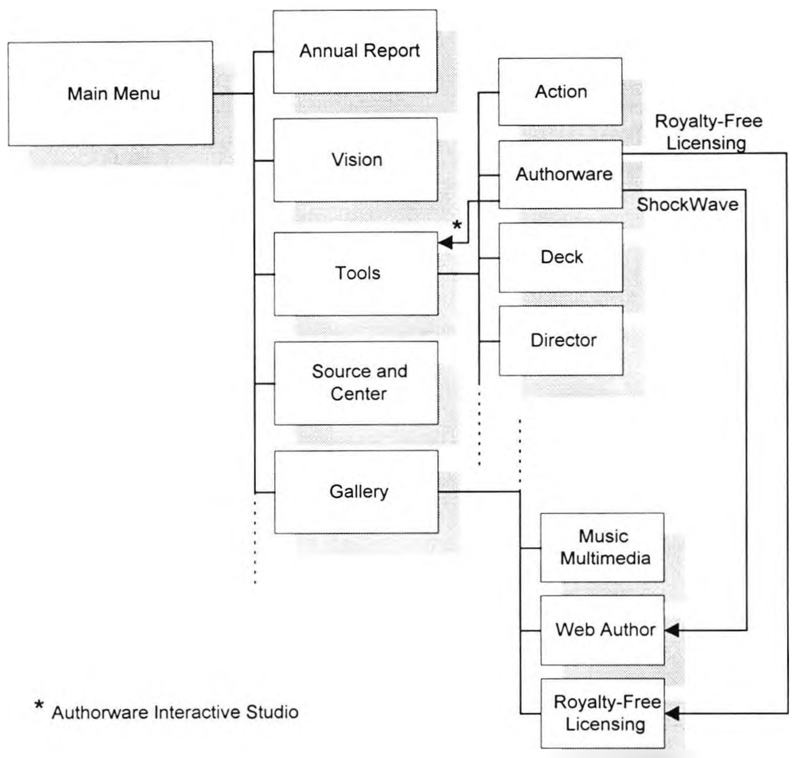


Figure 3.8 Part of the Macromedia Showcase Navigation Chart

Flowchart information design can be divided into four types of structures; linear, web, hierarchical and grid (Figure 3.9). Linear structures are best used for describing linear presentations, historical progressions, step-by-step instructions etc. A book is an example of linear structure and a multimedia example that takes on this structure is provided in the example of Figure 3.10. An example of a web structure is the World-Wide-Web. A web structure is generally haphazard and is best used for exploration or "surfing" than structured information. The hierarchical structure is the most commonly used structure. The Macromedia Showcase discussed earlier is an example application that employs a hierarchical structure, see Figure 3.7. Generally, the upper levels of a hierarchy are associated with general items, and the lower items with depth of specialization. From closer examination of Figure 3.7, the Showcase is in fact a combination of a hierarchical and a web structure, but it leans more heavily towards the hierarchical form. The grid structure is often used for databases or multi-parent heirarchical models. Even though a database often uses a grid structure to store its information, the presented information to users are often depicted in a hierarchical format for easier reference.

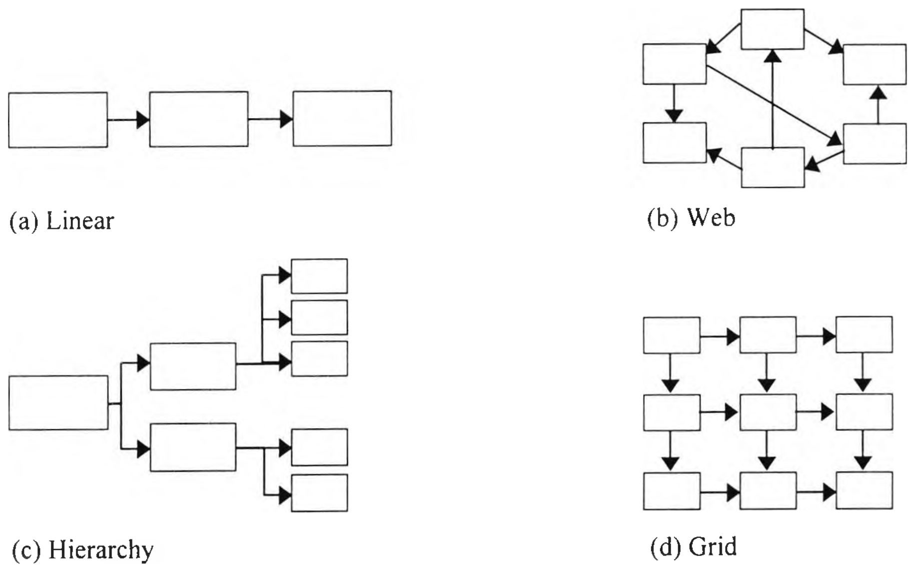


Figure 3.9 Some commercially applied structure types

The structure to use is very dependent on what is to be presented and sometimes no single structure but a combination of structures is best. In general, the linear and web structure are best allocated for applications that have a small information volume. With the large number of jumps to be made in a linear structure, users can become very frustrated when seeking a specific item of information down the line of a massive structure. While with an excessive web structure, it is easy to get lost in the vast sea of information as it is difficult to keep track of where one has been. The hierarchical structure however, can be used in practically any situation, small or large. While the grid structure is best for applications that contain an extensive database, though again, this is often only an internal representation rather than what is presented to users.

The question of breath or width applies equally to these forms of structures, as do the menu structures commonly found in most windowing applications today. In general, it is best to get users to their destination in the fewest number of clicks as possible, while presenting users with a reasonable number of options. The literature is somewhat mixed as to the "optimal" number of alternatives per frame but several principles stand (Norman, 1991). Norman suggest these principles:

1. Increase breath to the maximum practical level for linearly organized arrays, such as numbers, alphabetized list, month of years, etc.
2. For a non linearly organized list, the optimal number of alternatives will fall between 3 and 12 depending on the various user characteristics and system parameters.
3. The overriding principle is to provide a logical and intuitive organization of the alternatives.

Taking Miller's magical number 7 ± 2 (Section 2.6), the author proposes that for important information, users should not have to click or jump through more than 3 screens to get to it. No more than four to five jumps to 80 percent of available information and no more than seven jumps to 95 percent of the available information. Finally, taking Norman's figure of twelve to be the maximum 5 percent of jumps to available information.

Figure 3.10 gives an example of an application that uses both a metaphor, and a navigational system. The C/C++ Multimedia Cyber Classroom CD-ROM title uses the FrameViewer application to display its multimedia content. FrameViewer employs a book metaphor in its navigation and hence, C/C++ Multimedia Cyber Classroom is an extension of this. Like a book, this CD-ROM title has a table of contents which consists of chapters and appendices. The navigation between the chapters and pages (digital book) is very much like reading a book. For example, readers can turn from page to page and jump from one chapter to another as one does in a book. Even the appearance of the interface uses a page style metaphor. The left and right arrow keys at the top of page allows readers to move forward and backward a page, while the down arrow key to the right allows readers to make larger jumps between sections of the current chapter. Again, all three attributes that makeup a good navigational system are clearly present, see Figure 3.10.

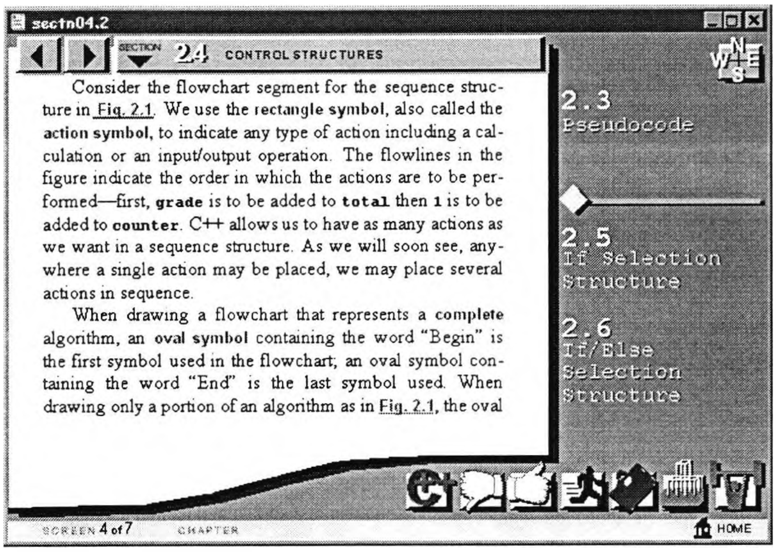


Figure 3.10 C/C++ Multimedia Cyber Classroom by Deitel & Deitel

The next section discusses a typical HMI model so as to provide system designers with a model of how users interact with computer systems. The intention is to provide designers with a better understanding of how users interact with computer systems that they may reflect this in their conceptual model of the system to be designed.

3.6 Principles of HMI Design

One objective of every HMI designer is to make the user interface transparent, so that users may get on with their required task rather than waste time on trying to figure out how the system works. Users do not want to use an interface, what they would like to do is to achieve their goals. Transparency of an interface is achieved when the conceptual model of the designer matches the mental model formed by users. Metaphors and/ or navigational system are often used to achieving this end. Metaphors and/ or navigational systems are however, only vehicles to transparency and it is the individual elements that make the sum of the whole. These individual elements and their relationship with each other should themselves be guided by general principles that the author proposes as fundamental in the development of an effective HMI. They are as follows:

1. *Visual Clarity.* Make the functional aspects of an interface visible and clear. Visual clarity in HMI means users are able to attain a strong conceptual knowledge of an application from looking at it's interface. By looking at an interface; the individual meaning, function and procedure of a visual element and how it relates to other elements, should be easily understood. Chapter 7 provides designers with some practical design guidelines on the presentation of visual elements, while Chapter 6 discusses icons.
2. *Encourage Exploration.* Visual clarity in an interface is usually not sufficient to provide users with a complete and accurate mental model. This usually comes with interacting with the application directly. To encourage interaction in users, the interface or application has to be designed to promote exploration. Users should be made to feel comfortable rather than feeling fearful of harming the computer or it's data when using an application. Section 3.5.2 of this chapter discusses a few methods of encouraging users to explore an application of which the 'undo' property is among the best.
3. *Provide Directness in Interaction.* A great method of providing interactive transparency in an application is to afford directness in interaction. Direct manipulation techniques are not new, they have been used in Graphical User Interfaces (GUI) interfaces for several years. In recent years, however, the shift has been towards a more Object Oriented User Interface (OOUI), where elements on screen behave like individual objects. OOUI is another step towards absolute directness as every property of an object is directly controllable from the object itself, as objects in the real world are.
4. *Place Users in Control.* Always put users in control of an application. An application is a tool and therefore should always be in the constant control of the user. For example, never give an application a long processing duration without giving users the option to cancel it at any given time. If users have to constantly wait for computers to complete a job, even if it was executed by mistake, they could become extremely frustrated and dissatisfied. Experienced users prefer being in control more than novices and as such, controllability and customizability are even

more important. Provide for customizability, as users are different and they each like to work differently. The upcoming version of the Mac OS 8 (MacUser, 1996) sees customizability as being a very important element of the desktop interface. A scaleable desktop is to be featured in its next OS to provide users with easier customizability. Users will be able to customize the look and behavior of their workspaces.

5. *Consistency.* It is one of the most important design principles and one that is referred to repeatedly in this thesis. It applies to HMI design in every aspect of presentation, behavior and action procedure. Consistency assists users in learning general concepts about a system, it instills predictability and thus builds up user expectations of a system. Consistency however, is not confined to within an application. Consistency between applications for example, is commonly found in applications running on the same platform where standards have been established. In Microsoft Windows applications for example, even such diverse applications as drawing, word processing and database use the same short-cut keys for copying, cutting and pasting (Ctrl-C, Ctrl-X, Ctrl-V respectively). Irrespective of what users would like to copy, cut or paste; be it text, drawing objects or database table, the action is the same. Due to such consistencies, transference of learning between applications is made possible. Predictability and user expectations are also reinforced.
6. *Informative Feedback.* For every user action, there should be an accompanying system feedback. Without feedback, users may not know if they have achieved their intended task. For example, take the DOS delete command. Users are not given clear indication as to the accomplishment of the delete task. All users see is a new command prompt line after the delete action. In order to check if the file has indeed been deleted as intended, users have to list the directory the file is supposed to be in to find out if it still exists. The hourglass icon often seen in Windows application when a system is performing a task is a good example of informative feedback. Without the hourglass cursor icon, users might not know that a system is busy and get frustrated when they try to execute the same action repeatedly, to no avail. Worse still, the action might be repeated after the system becomes available and the user has to delete the unintended repeats. In order for feedback to be effective, it

should also be immediate. Sometimes delayed feedback is as bad as having no feedback. Drawing applications that use a pen input device for example, cannot afford to have delay in the drawing motion of users and what is seen on the screen. Feedback in this instance has to be immediate, otherwise the tool is ineffective.

7. *Reduce Cognitive Load.* Good HMI designers always take user strength and weaknesses into their design considerations. One area where computers could assist users is in the area of cognitive load. As proposed by Miller (1956), human short-term memory is good with seven, plus or minus two chunks of information. Users therefore, should never be forced to remember and repeat what the computer could be doing for them, unless it is the intention of the application. Another area where computers could assist is in the area of mathematical calculations. Instead of users having to to perform a mental calculation, applications could instead be designed to perform them automatically. Humans are also far better at recognition than recall. Where possible, provide users with a list of options rather than forcing them to recall from memory. Chapter 2 on HMI Psychology provides detailed information on human strengths and weaknesses. It also provides similar analysis about computers and how they can be made to complement each other.

3.7 Conclusion

An application is intuitive when the user's mental model reflects the designer's conceptual model. The latter comprises object relationships, presentation (look) and interaction (feel). The synergy of these three areas provides the user with a mental model of the application in use, which determines the overall usability of the application. Planning and developing these areas well, will provide users with a more accurate mental model of the application, thereby improving its usability. The use of metaphors and/ or navigational systems in HMI has been discussed. These two elements assist users in understanding the structure of the application. A user HMI model and design principles have been worked out to assist designers in developing applications that are user friendly.

In the next chapter, the author investigates input and output devices, which dictate the 'feel' of an application.

4. Interface Methods and Input/ Output Devices

4.1 Introduction

We perform a wide variety of tasks on a computer and the ways we can do them fall into a small number of classes. Different input and output (I/ O) devices support these activities to a greater or lesser degree. A well-designed interface will supply those I/ O devices that best support the expected activities. This chapter discusses topics on I/ O devices, development and trends in I/ O devices, and how best to use them in a given task activity.

With the advent of increased capabilities of computers today, the practice of using a standard 102-key keyboard and a two-button mouse as sole input devices is disappearing. Likewise, computer monitors are going out of date as being an exclusive output device. Even though scanners or printers could be placed in the above two I/ O device categories, this chapter will only consider devices that are used in an interactive manner during the human computer communication process.

The chapter begins by providing a general overview of I/O device trends and developments in relation to the types of computer interfaces. It then works through each I/O device category in turn, looking at the developments made within them. From this, a summary comparison table is provided to cover the input devices. This table provides a basic first step method in the selection process of existing I/O methods to suit task requirements. The next step in the selection process would be user testing, which this chapter does not have the scope to discuss as the requirement would be too specific in nature. The chapter closes by providing an example of how some of the I/O devices covered herein, could be used together to form an integrated system. Such systems are undergoing research and some are commercially available, but presently at a high cost.

4.2 Interface Methods

Research in the area of input/ output (I/O) devices centers around two ends of the communication channel between humans and computers. At the human end, the communication channel is restricted by our human perceptual abilities, thought processes and physiology (Chapter 2). At the computer end, the communication channel is limited by the input/ output devices we are capable of constructing. The aim therefore is to find a common ground between the two ends of the already narrow communication channel in the development of usable input/ output devices. Usability here, relates to how well the I/O devices map our limited human communication channel and to which of these human senses or combination of senses we find easiest to use in carrying out a specific task.

In an ideal case, the development of I/O devices would begin with knowledge on human communication drawn from studies of psychology, physiology and human-machine interaction. This is followed by carrying out a task analysis on the type of interaction methods needed in performing the task at hand. Once this is established, the I/O hardware is designed and constructed to the specification of the task analysis and human communication studies. The I/O devices created are then placed through rigorous testing in near, if not real-life settings to test for usability. Any short comings on usage are recorded and new designs implemented to eliminate them. While total elimination is not a feasible option, designs should attempt to minimize any hindrances.

The I/O devices created using the process above are generally specific to applications for which they were created or in some instances they may be applied to applications with similar interaction requirements. In the commercial world, however dedicated I/O devices would not usually be cost effective and therefore require that development be of a generic form. This is the case with computer keyboards and mice, the two most common input devices found on computers today. The design of I/O devices are also dictated by current interaction styles of which the following exists; command languages, menus, natural language, direct manipulation, virtual reality and the use of agents.

4.2.1 Command Language Interfaces

Command language interfaces are the original form of computer interface. They were commonly used by engineers and programmers and still are preferred by some of them. An example of a current command language interface is Microsoft's Disk Operating System (DOS), with its notable C:> prompt. Command languages are concise and unambiguous but they have to be learned, hence making them quite difficult for immediate use. Command languages usually employ the keyboard as an input device but voice recognition devices are making some in roads in this area.

4.2.2 Form-Filling Interfaces

Form filling interfaces, uses an interface style, where a number of separate choices are simultaneously presented, but can be made in any order. Generally, this form of interface is used for data entry into a database.

4.2.3 Menu-Based Interfaces

Menu based applications regularly employ pointing and selecting devices like the common mouse in their interactions. The keyboard, though used less frequently by novices is commonly used by the more experienced for this end. Menu selection using the keyboard is generally done by using key combinations as short-cuts to menu options. With windowing environments on the increase, icons or toolbars have added to the list of existing text-based menus. Generally, the preferred input device for the selection of icons is through the use of a pointing device, like the mouse. Advancement in sound board technology has made possible an alternative in menu selection and command language interfaces. For example, SoundBlaster soundcards provide users with the opportunity to interact in the Microsoft Windowing environment using spoken commands through it's Voice Assist voice recognition software (Davenport, 1993).

4.2.4 Natural Language Interfaces

Natural languages often employ artificial intelligence (AI) technology in the recognition of users natural language communication with the computer. Requests can be made by typing in commands on a keyboard. The computer processes the request using some form of AI technology that generally incorporates use of neural-networks, a knowledge-based system or a combination of the two. More recent advances in computer technology employ voice pattern recognition on top of this. This technology enables users to speak to their computers, bringing the communication closer to human forms of communication.

Natural language features are being applied in new versions of programs from Microsoft, Lotus, Novell, and other software vendors. Microsoft's Office 95, for example, contains an "Answer Wizard" that lets you type in anything ranging from a few words to a complete statement or question in search of help. Likewise, Lotus's WordPro for Windows has a similar feature called "Ask the Expert." Novell is planning to incorporate similar natural language features in its Perfect Office (Byte Magazine, 1995), in the form of interactive "coaches," templates, and "quick task" routines. Novell is also introducing voice recognition natural language queries in its 1996/ 1997 version of Perfect Office.

Current working natural languages are restricted to a subset of natural language and if voice is to be used in the communication process, short pauses between words are required as current voice recognition systems have yet to support continuous speech. The current use of a subset language instead of a fuller vocabulary, reduces the errors produced and decreases the pause time needed between words. However, as computers improve in processing speed, voice input technology should allow normal speed speech.

4.2.5 Direct Manipulation Interfaces

The direct manipulation concept, which is an advent of Graphical User Interfaces (GUI), is based on analogies to existing human skills of pointing, selecting, moving and manipulating objects in a GUI environment. Object Oriented User Interfaces (OOUI) like Windows 95, OS/2 Warp and System 7 take this concept a stage further, whereby all graphical elements in these environments are built up of objects that have properties like objects in the real world. Selecting an object with the mouse button causes a floating menu to appear which allows the user to change the properties of the object or execute frequently used commands for the object selected, for example, 'cut and copy.' Figure 4.1 depicts an example of direct manipulation that closely resembles the way we work in the real world. It shows a selected folder being dragged into a waste paper basket for deletion. Currently, the keyboard and mouse (or similar pointing device) are the most frequently used input devices in direct manipulation environments.

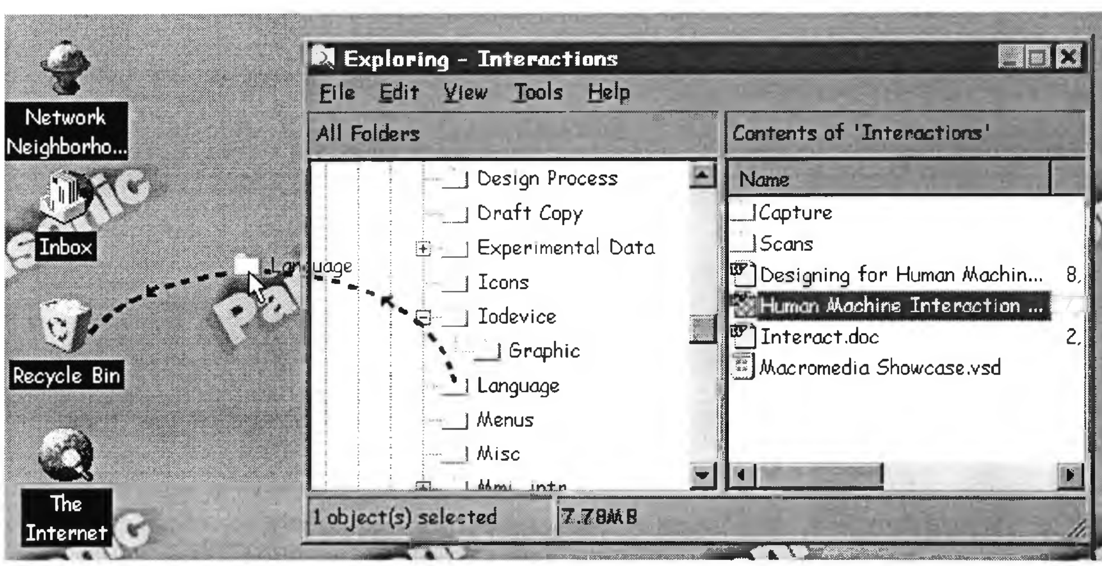


Figure 4.1 Direct-Manipulation Interface with a drag and drop approach to deleting

Current OOUI environments are generally 2D in nature, even though some, for example, Windows 95, provide icons and buttons that are 3-D in character. However, the 3-D interpretations in these environments are still restricted to a single plane and do not provide views from different angles. Some OOUI applications provide their users with 3-D-like working environments, like the 'Navigator' user interface by Packard Bell or the popular Magic Cap interface by General Magic. Magic Cap, for example, is an object oriented operating system designed for PDAs (Personal Digital Assistants). Figure 4.2 shows an interface example of the Magic Cap operating system (Pen Computing Magazine, 1995). Most interfaces of this nature, tend to resemble illustrations or cartoons. Microsoft has recently announced that it is going into the computer hardware foray with its first graphics chip, codenamed Talisman (CNN Computer Connection, Aug. 1996). With the release of Talisman, Microsoft intends to introduce a 3-D version of its Windows operating system.

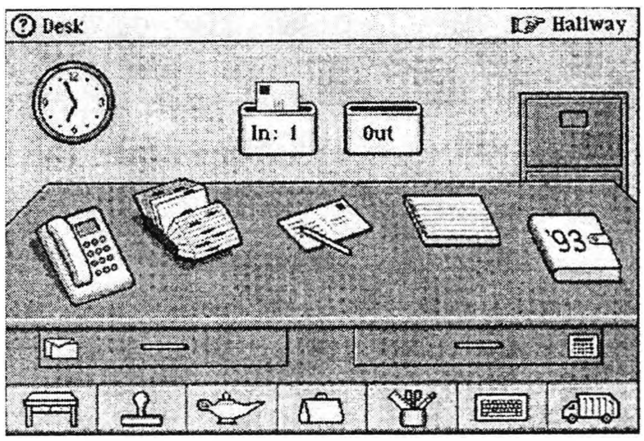


Figure 4.2 Magic Cap OS by General Magic

4.2.6 Virtual Reality Interfaces

Virtual Reality (VR) interfaces, unlike the previously discussed interfaces, are 3-D in every respect. VR interfaces bring direct manipulative interactions a stage closer to how we normally interact with our environment. They provide users with the opportunity to totally immerse in so called 3-D computer generated world, thereby enabling users to interact with objects as one does in the real world. Compared with the interaction styles discussed earlier (Sections 4.2.1 to 4.2.5), typical VR I/O devices are a departure from the conventional computer monitor, keyboard and mouse. Instead, they typically consist of a stereo pair head mounted display with 3-D orientation sensors to monitor the orientation of the viewers head and a 3-D input device with typically six degrees of freedom for navigational and interaction purposes.

4.2.7 Agent-Based Interfaces

The idea of agents originated with J. McCarthy in the mid 1950's, and the term was coined a few years later by O. G. Seldfridge (Laurel, 1990), when both were working together at MIT. The concept was that a computer could be given a goal and it would carry out the required task to that end, querying for details or advice where necessary from the user. According to Brenda Laurel (1990), one of the leading researchers in agent technology, "agents can be defined as a character, enacted by the computer, who acts on behalf of the user in a virtual (computer-based) environment."

The incorporation of agents in applications is still in its infancy. Applications are beginning to incorporate them in the form of "Help Wizards" or "Experts", as can be seen in prevalent applications by Microsoft or Lotus. Presently, the addition of agents has not changed the "look" of the common Windowing GUIs. However, with future releases of more sophisticated agents, one might start to see the emergence of a different GUI and different ways of interacting with computers. By simulating the social interaction of real life, agents try to present an environment that is more familiar than graphical desktops and command-line prompts. Today, GUIs are at the center of interaction but as the use of smarter and more capable agents increases, it is the agents that will be seen to be more central to our interactions with computers.

The agents introduced by the likes of Microsoft and Lotus in the form of "Answer Wizard" and "Ask the Expert" respectively can be categorized as advisory agents. They do not perform any tasks, but are there to assist a user in the form of advice or instructions in performing a task. These agents currently are in a basic form, as they are there to provide assistance at the users request and know nothing of their users. Future, smarter agents will, however, incorporate a user database that will be used to store ongoing knowledge amassed about the user in terms of user work patterns and preferences. This knowledge-base can be used by an agent to provide better and more timely advice to their users.

An example of how such an advisory agent can change the look of the common windowing GUI and interaction style can be seen in Microsoft's add-on interface for Windows, call Bob (Figure 4.3). The most visible interface element of Bob is its little cartoon-character personalities that act as user guides and are the center of Bob's "social interface." The Bob interface has not had a big influence in the interface industry but it has several crucial user-interface innovations that could change the way the next generation of computer users expect their machines to behave. Another big player of agent-based interfaces is IBM, in its quest for Human-Centered Computing. IBM is using Actors in its visible manifestation of agents, and Charlie (Figure 4.4) is the first of such characters. Actors are to use speech as well as visible facial clues to indicate the progress of agents in carrying out a user request. Shipping versions of Charlie are expected to be less realistic due to the computationally intensive nature of Charlie. Furthermore, the less realistic version of Charlie would be less intimidating to users.

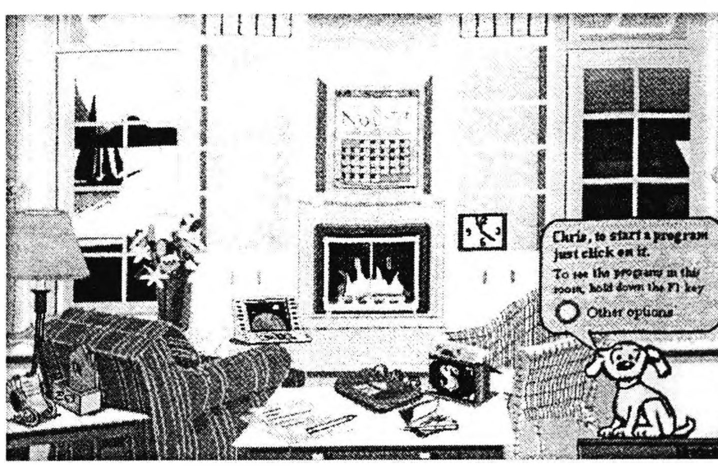


Figure 4.3 The Bob interface, by Microsoft

Figure 4.4 A visible manifestation of an agent call Charlie, by IBM

Another form of agent is the assistant agent. Assistant agents are more difficult to develop as they often act without direct feedback from users. Typically, an agent of this kind is implemented by coupling an artificial intelligence program to a graphical representation of a character or object which represents the function of the program. An example of an assistant agent is one that manages a user's electronic diary or electronic communications like E-mails. Such an agent would be able to carry out tasks that a personal secretary performs, like reminding, scheduling, filtering, sorting and organizing. While this type of agent is more powerful, their potential for disaster is far greater as such agents are given the ability to perform tasks unaided. Commercial examples of agent based applications are already available on the Autonomy Web site (www.agentware.com). There is a Guardian Angel (content censorship for children), browsing agent, email handling agent and a news editing agent. The agents employ a neural network technology in considering words as symbols, and builds rules about the probability of them coming together in certain patterns. The agents are therefore, far better at finding web sites that are more appropriate to a search.

Interface agents draw their strength from the naturalness of the human communication metaphor in terms of both cognitive accessibility and communication style. Such interfaces will draw other forms of natural human communication methods such as natural language processing, computer speech generation and speech recognition for the next generation of applications.

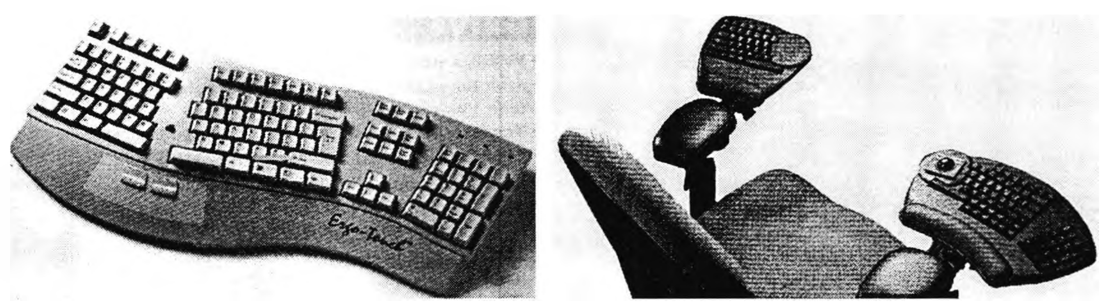
4.3 Hardware Input Devices

4.3.1 Keyboards

4.3.1.1 Standard Keyboard

Keyboards are found on almost every desktop and notebook computers, and there is generally scope for improvement. On notebook computers, improvements are limited to the layout of the keyboard, size of the keys, key travel distance and angle of inclination of the keyboard. The latter is commonly achieved by having hinges on the rear end of the notebook to lift the keyboard to an angle.

Recent significant improvements in keyboard design are found with desktop keyboards, where space is not a premium. Major improvements include features that reduce repetitive strain injuries (RSI), which can develop as a result of prolonged and intensive keyboard use. The three most popular features to counteract RSI include split angled keyboards, angled keys and built-in palm rests. The typical split angled keyboard splits down the T, G and B line, separating the well accepted left-hand keys from the right-hand keys. Each of the split keypad is set at a 90-degree angle to the typist forearm, which lets users keep their wrists and fingers in a straight line when using the keyboard. Additionally, some keyboards, like the Microsoft Natural Keyboard, angle each key to the contours of a typist hands. Figure 4.5 depicts a typical ergonomic keyboard (PC Magazine, 1994) incorporating the features mentioned above. Next to it, a similar keyboard split entirely in two and mounted on each end of the arm-rest of an office chair from Workplace Design (Byte Magazine, Feb. 1990).



(a) Powermark Ergonomic Keyboard (b) Floating Arms Keyboard

Figure 4.5 Ergonomics Keyboards

Other features to be found on newer keyboards include special keys and built-in mouse pointing devices. In terms of special keys, many have Windows 95 combinations similar to the commonly used Alt-Tab combination for switching between open applications. Microsoft's Natural Keyboard includes a special key for the yet to be released Chicago operating system, that is to supersede Windows 95. With respect to built-in mouse trackers, the very latest keyboards include touch sensitive trackpads which allow users to control their mouse pointers by gliding their finger over it. Previous to this, keyboards included the TrackPoint pointing device (especially on notebook computers) made famous by IBM in their Thinkpad range. The Key-Mouse has yet to be adopted as an alternative. Movement of the mouse cursor is achieved by small movements of the J-key in the required direction, very much like that achieved by the TrackPoint pointing device. Finally, the first ever built-in alternative to the conventional mouse, and still found in extensive use today, is the trackball. Further discussion on mice and it's alternative is covered in Section 4.3.2.

4.3.1.2 Chord Keyboard

The design of keyboards is still evolving, others, like the BAT personal keyboard from InfoGrip, Inc. and Accukey from Vatell Corp. stray away from the conventional concept of a keyboard. The BAT Personal Keyboard lets typist use chord combinations to achieve full keyboard functionality with only seven keys. Figure 4.6 shows both a left and right-handed version of the BAT keyboard (Byte Magazine, Jan. 1995 & July 1994). The BAT keyboard is difficult to use initially because there is not a one-to-one mapping of keys to characters as with a normal keyboard. In order to use this keyboard proficiently, one has to remember the chords for all the characters. It can take anywhere from a few hours to a couple of weeks to become proficient with the BAT keyboard. This device is essentially the same as the one used by court stenographers to record court sessions. Here, the difficulty of learning is traded with speed of typing. Likewise, the Accukey keyboard follows the same principle as the BAT keyboard, with the difference that both hands are used in the touch typing process.

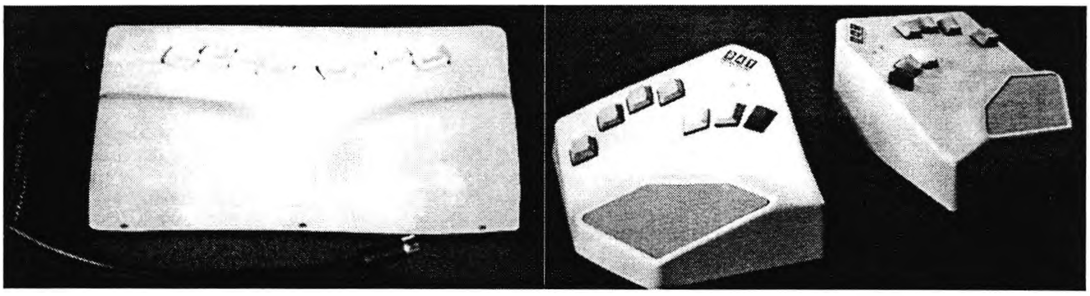


Figure 4.6 The Accukey keyboard (Left) and the BAT Personal Keyboard (Right)

Another keyboard that borrows the chord keying method of typing is the Twiddler from Handykey Corp. (Byte Magazine, June 1994). Twiddler (Figure 4.7) is different in that it also supports a mouse pointer and doesn't require a desk, as it is a hand-held device. Twiddler fits comfortably into one's hands, secured by an adjustable

Velcro and nylon strap. The mouse pointer in the Twiddler is based on an electrolytic tilt sensor that is sealed inside the device. By pressing the mouse button on the top of the unit and pointing with the index finger in the direction required, one can control the cursor on the screen. Handykey claims that most people can learn the alphabet on the Twiddler in about 3 minutes and master the device in about 10 days.

Figure 4.7 Twiddler hand-held mouse/keyboard

4.3.1.3 Keyboard for Children

Even children are receiving some attention from computer manufacturers like Compaq who is in a joint venture with Fisher-Price (maker of children's toys) in developing new peripherals aimed at young children. The Wonder Tools (PC Magazine, Mar. 1995) as they are called, includes a keyboard that has everything a standard keyboard has but designed specifically for pre-school children to interact with a PC. The keyboard keys are oversized, with special keyboard functions for easy navigation and frequently used commands like home screen and exit keys.

4.3.2 Mice and its alternatives

4.3.2.1 Common Mouse

Mice are the second most common input device found on PCs and they still account for about 80% of all pointing devices sold (Windows Magazine, Jan. 1996). It was introduced in 1982, and since then, it has seen a steady growth in popularity. The mouse, which is a simple device, it has a partially exposed rollerball that touches two internal rollers, representing horizontal and vertical movement of the cursor. The mouse, or an alternative, are almost essential for the latest graphical operating systems like Windows 95, NT, OS/2 Warp and System 7.

Mice usually have two or three buttons and motion resolutions of about 200 counts per inch (cpi). The very latest have an ergonomic feel to them with additional software to customize the appearance, motion and double clicking speeds of cursors on screen and pre-programming of the third button to represent a certain keystroke. Honeywell released an innovative mouse tracking mechanism in 1992 employing two plastic, disk like opto-mechanical feet (see Figure 4.8). The friction-less internal design of this mouse eliminates the need for any cleaning.

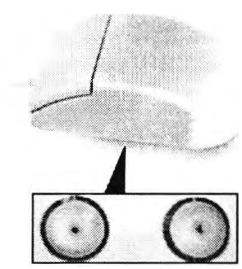


Figure 4.8 Honeywell's alternative to the conventional roller ball tracking mechanism

The latest mice have become cordless, for convenience. Most of these mice employ the latest infra-red technology to communicate the position of the mouse to a receiver which is then relayed to the computer via the conventional serial port or PS/2 mouse port. Some notebook computers now in-build IrDA (infra-red data association) ports. IrDA has become an industry-standard for software packages employing this technology. With Windows 95 having full IrDA support, more IrDA I/O devices like mice, keyboards and printers are anticipated.

4.3.2.2 Trackballs

Alternatives to the traditional mice abound. The trackball is one of the first contenders to the mice. This concept is very similar to the common mouse, except it is the ball that tracks the position of the mouse cursor, and is moved directly by the user rather than being moved through the motion of the mouse over a flat surface. The advantage of the trackball over mice is that it require considerably less work space. Most good-quality trackballs have resolution of between 200 cpi and 400 cpi. Microsoft recently released the "EasyBall" trackball (Figure 4.9) for young children, who have less well developed motor skills than adults (PC Magazine, Jan. 1994). To make it appealing and functional, the EasyBall has a central brightly coloured ball that measures 10cm in diameter with a single large button and a sturdy base.

Figure 4.9 EasyBall trackball by Microsoft

4.3.2.3 MousePen

Other alternatives to the mice include the MousePenPortable from Appoint Inc. Using a MousePenPortable is very much like using a pen. The technology, however, is not new, as it incorporates current mice technology. MousePenPortable has a roller ball at the tip of its pen just like that found in a mouse, it incorporates two buttons and has a dynamic resolution of 50 cpi to 1000 cpi.

4.3.2.4 TrackPoints

TrackPoints, a popular alternative to mice, is commonly found in most IBM and Toshiba notebook computers. The TrackPoint device looks very much like an eraser head and is also commonly called an integrated pointing stick. It is generally placed in the middle of the home row keys of a keyboard and used in conjunction with two buttons placed below the spacebar. Pushing or pulling the TrackPoint in the desired direction causes the on screen cursor to respond appropriately. TrackPoint is omnidirectional and pressure-sensitive; the harder you press, the faster the pointer moves.

4.3.2.5 Key-Mouse/J-Mouse

The Key-Mouse from KeyTronic (Computer Buyer's Guide, 1995), as mentioned in Section 4.3.1.1 is another option for computer keyboard manufacturers interested in incorporating a pointing device in their keyboards. Under normal circumstances of typing, for example, the J-key acts as usual, but when a key combination like Ctrl-J (programmable), is depressed, the J-key becomes a joystick. Cursor motion is achieved in the same manner as the TrackPoint pointing device described above. When the joystick is enabled, the S, D, and F keys become mouse like buttons. Another version of the Key-Mouse is the J-Mouse by Keyboard Company. The underlying technology is the same, but the activation of the "Mouse" is different. The J-Mouse is activated when it is pressed and held for a short duration in time. With the J-Mouse, the spacebar functions as the mouse button.

4.3.2.6 Touchpads

Apple's new Mac PowerBook 500 notebook is one of the first computers to incorporate the innovative touchpad/ trackpad pointing device that essentially has no moving parts. The finger operates it. Touchpads are set to become the next generation of pointing device in notebook computers. BIS Strategic Decisions predicts that touchpads will account for 70% of all integrated pointing devices by 1998 (Windows Magazine, Jan. 1996). The technology is based on field distortion sensing, a capacitance sensing technology licensed from Cirque (Salt Lake City, UT), rather than pressure. The pad contains two layers of fine electrical conductors arranged in a grid that generates an electrical field over the touchpad surface. When a finger is placed on the pad, the capacitance of the layer changes. The exact location of the fingertip is determined by sensing the strength of the distortion at each conductor. This technology is very intuitive as finger motion correlates very well with cursor movement and instead of clicking a mouse button, the user merely gives a single tap on the surface of the pad. Even double taps are supported as representation of double clicks. Figure 4.10 depicts a three button Glidepoint trackpad from ALPS Electric Ltd. Typical trackpads have resolutions ranging from 400 cpi to 1000 cpi.

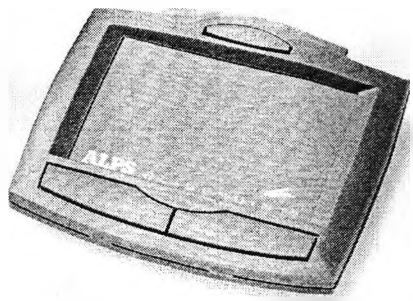


Figure 4.10 The ALPS Glidepoint trackpad

Another touchpad by Synaptics (San Jose, CA) takes advantage of capacitance-sensing technology, but has extended the pad's capabilities with proprietary algorithms for pattern recognition and adaptive analog VLSI technology. The TouchPad not only senses motion of any kind, but also senses pressure or even the distance of a fingertip from the pad's surface. This technology will support pressure-based functions such as handwriting, painting, and other applications that usually require a pressure-sensitive graphics tablet.

4.3.2.7 Feet Mouse

All the pointing devices described thus far employ a hand as a medium to input, but a new input device call the No Hands Mouse (Figure 4.11) is an alternative to RSI sufferers (Laptop Buyer's Guide, 1996). No Hands mouse by Hunter Digital (CA, US) is designed for mouse-intensive applications and employs foot pedals as a means of controlling the mouse cursor. The cursor control mechanism used on one of the foot pedals is very similar to IBM's eraser head TrackPoint device. This foot pedal features a proprietary 360° pressure sensitive mechanism, allowing the user to control both the mouse direction and speed, while the other foot pedal is used for clicking.

Figure 4.11 No Hands Mouse by Hunter Digital (CA, US)

4.3.2.8 Joystick

The PC joystick is one of the most frequently used input device for the PC games industry. A mouse can be used as an alternative, but joysticks are much more frequently used to provide fast and direct input. Most joysticks have at least two degrees of freedom, left or right and forward and backward. Such motion is typically sensed using potentiometers. Some joysticks provide a third degree of freedom by incorporating a stick that can be twisted clockwise and counterclockwise or fourth with the addition of vertical up and down motion of the stick. The games industry, however is not the only main users of joysticks as they are also commonly used in the control of machinery and robots.

4.3.2.9 Recent Pointing Device Technologies

The GyroPoint from Gyration (Personal Computer World, Feb. 1996), is the first mouse to be built on the principle of the gyroscope and represents the latest in mouse technology. The GyroPoint looks and can be used in every way like an ordinary mouse but has an added difference when picked up. In air, the GyroPoint can be used to point and click with a natural wrist motion. A cordless version is available and claims to work at distances up to 23m. Unlike IrDA devices, GyroPoint does not require a direct line-of-sight. The GyroPoint is comfortable to use and the cordless version is ideal for presentation. The prolonged use of GyroPoint in air however, could be tiresome.

4.3.3 3-D Input Devices

Some of the devices discussed here could fall into the previous category. However, they are grouped here for the sole reason of being able to provide 3-D input. 3-D input devices are suitable for applications like computer graphics, 3-D CAD, 3-D games, animation, and virtual reality. Most of the devices discussed here have been designed specifically for 3-D applications. However, all have the added ability to be used as a conventional 2-D mouse, but with varying degrees of ease.

4.3.3.1 Transmitter-Receiver Based 3-D Input Devices

Logitech has created a 3-D mouse that operates like an ordinary mouse and also as a 3-D input device (Figure 4.12). Logitech's 3-D mouse provides six degrees of freedom, giving control in the x, y, z axes as well as in the pitch, roll and yaw orientations. The device in the background of Figure 4.12 is responsible for tracking the mouse position and orientation as the mouse is moved through the air. The 3-D mouse is constantly transmitting ultrasounds at the corresponding receiver, which then employs triangulation techniques in determining the transmitter's location in 3-D space.

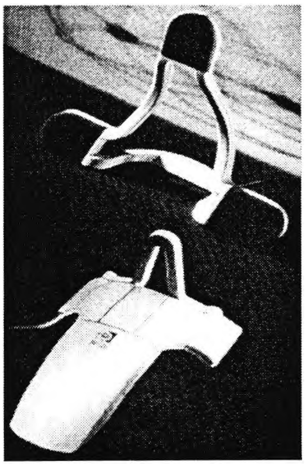


Figure 4.12 3-D Mouse from Logitech

As the name suggest, the RingMouse (Byte Magazine, Feb. 1996) is worn like a ring on the index finger as shown in Figure 4.13. The RingMouse uses a velcro strap as an attachment fitting. It is a wireless unit and operates like a two-button mouse. The

RingMouse has a device that sits on top the monitor. This has sensors that triangulate the mouse's position and detects its movement. Hovering the RingMouse hand over the keyboard translates into cursor activity on screen. The RingMouse also supports 3-D cursor movements.

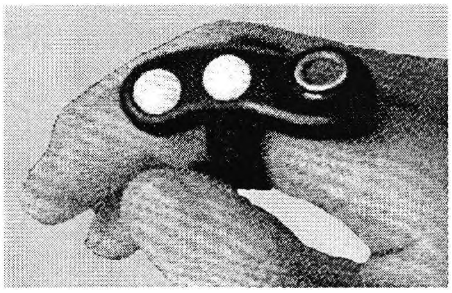


Figure 4.13 Spectrum RingMouse from Kantek, Inc.

Alps 3-D mouse (Byte Magazine, June 1994) is a hand-held pointing device that lets the user directly manipulate and control the screen cursor in a 3-D workspace. As with the two previous pointing devices, the Alps 3-D mouse employs triangulating sensors to determining the position and orientation of the mouse in 3-D space. The Alps 3-D mouse has a unique ergonomic design (Figure 4.14), providing six degrees of freedom as x, y, z, yaw, pitch and roll. It is suitable for applications requiring precision and intuitive control in 3-D space. The mouse can also emulate a conventional 2-D mouse.

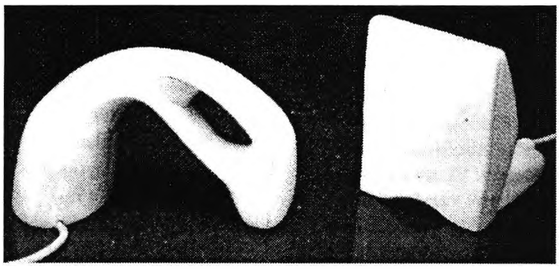


Figure 4.14 Alps 3-D mouse from Alps Electric Ltd.

4.3.3.2 SpaceBall

The 3-D Spaceball (Byte Magazine, Nov. 1992) diverges from the previous 3-D pointing devices in that it does not have a specialized sensor to track the pointing device in a 3-D arena. Instead, the Spaceball manipulates screen objects about the x, y and z axes simultaneously with a touch. Increasing the pressure on the ball (Figure 4.15) increases the speed of an object's rotation. In essence, the spaceball is very much like a 3-D six degrees of freedom joystick.

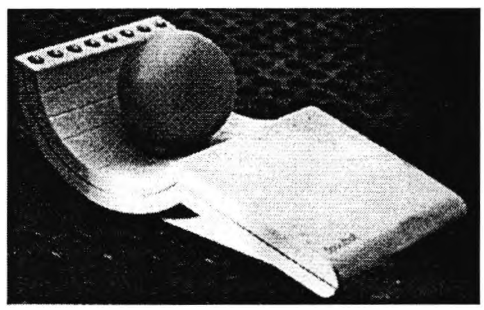


Figure 4.15 Spaceball from Spatial systems

4.3.3.3 Electrostatic Devices

An innovative input technology is being researched by Hewlett-Packard (HP) development laboratory, which harnesses the electrostatic fields in a range of input devices. Instead of using awkward input devices, researchers (Dr. Peter Rogers of HP) are trying to utilize the space around devices as a method of input. The underlying principle is that as users distort the electrostatic fields by moving through them. The field distortion can be measured as a reduction in current, and this reduction through space can be seen as a directional input. This, in principle, is inaccurate for any practical use but two methods of improving the accuracy are being investigated.

The first method employs two electrodes, one of which oscillates and the other acts as a receiver, with the user acting as the 'ground'. This, according to the investigators, increases the accuracy of the receptive electrodes. The second method is being use in conjunction with 3-D and VR technology. By placing electrodes around a monitor, developers believe they can create a hand position relevant to control a 3-D arena, allowing users to manipulate an image in 3-D without using conventional input devices.

4.3.4 Pens

Pen input devices have actually been in existence longer than the mouse. They were initially used on terminals attached to mainframes over 25 years ago, but have been less successful than the mouse device, for example. However, one advantage of pen-based computing today is its support at the operating system (OS) level instead of having to be application specific. Microsoft Windows has a pen extension to its OS (Pen for Windows). Pen for Windows provides support for mouse actions like move, click, resize, etc. It also supports handwriting recognition and conversion of handwritten text into normal text. Handwriting recognition is, however, based on the user writing in printed text format rather than in script. Pen Extension also provides the use of pen gestures in editing operations. Figure 4.16 depicts some pen gesture examples from Pen Extensions for Windows.

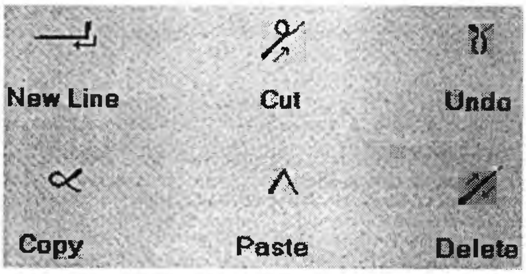


Figure 4.16 Text editing gestures provided with Pen Extension for Windows

Pen-based systems can be divided into three categories - pen slates (notebook variant), Personal Digital Assistants (PDAs), and specialized vertical market pen systems. Developments in 1995 clearly show that the pen computing scene has shifted. The number of notebook PC's with pen options has not increased and operating systems updates like Microsoft Windows 95 are not providing pen services components. Companies like Compaq and Apple have ceased production of pen-based notebooks.

Whilst pen notebook PC's has thus moved into a somewhat uncertain future, PDAs are becoming more important. This is so much so that PDAs have been described as the 'Fourth Wave' of computing, that will be driven by the continuing trend of miniaturization and the desire for increasingly more comprehensive access to information. Access will no longer be confined to the desktop/ notebook PCs with a modem. Instead, wireless communications are seen to be the future of PDAs, from cellular to radio frequency packet and from wireless local area network to paging.

Pen-based devices are targeted at specific markets that have the greatest requirement for pen input, such as delivery services, insurance agencies, hospitals, and police departments. In essence, it targets those who needed portable computers. Therefore, it is not surprising that PDAs are one of the most used pen input devices in the computing industry. PDAs play a critical part in reaching goals, such as better communications systems, data collection, decreased costs and increased productivity. Recently, (June 1995 issue of Pen Computing Magazine from the U.S.), there were found to be over 40 different pen-based systems available. Most utilized dedicated pen based operating systems (OSs), the more popular ones include General Magic's Magic Cap OS (Sunnyval, CA), Apple's Newt-OS (Curpertino, CA), GEOS from GeoWorks (Berkeley, CA), PenPoint from Go (Foster City, CA), PenDOS from CIC (Redwood Shores, CA) and PenRight (WestLake,TX), (Pen Computing Magazine, June 1995). PDA's have good potential, but the reality leaves something to be desired. Unfortunately, they are still products of an immature technology. Prices are high, handwriting recognition is marginally effective, and communications are incomplete.

4.3.4.1 Pen Technology

Although the key issues are almost all software-related, some recent hardware changes to pen-based systems have achieved greater ease of use with the hardware product. Currently, there are two main streams of pen-based devices, digitizing tablet and light pens. Light pen systems employ a direct method of input, as with the users writing directly on a screen. While digitizing tablets systems employ a tablet in the input process, the tablet being a representation of the screen. However, the latter has changed with the advent of pen-based notebook PC's and PDAs, as was explained in Section 4.3.4.

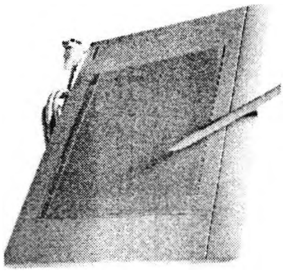


Figure 4.17 ArtPad from Wacom Co., Ltd.

Figure 4.17 depicts an ArtPad pen/ tablet from Wacom (Personal Computing World, Feb. 1996), this is typical of digitizing tablets available today. A digitizing tablet has three major components: a tablet, a pen (or stylus), and a controller. The tablet consists of a sensing area that detects the pen position. The pen is used as a pointing device. It can have a transmitter that sends a signal to the tablet (receiver), or it can receive signals from the tablet. The tablet controller detects the pen by scanning the tablet's active area. Detections are then translated into a series of x, y coordinate pairs. Current designs are generally based on the use of electromagnetic fields, electrostatic/ capacitive films, electrostatic grids and resistive films.

The underlying technology employed by the ArtPad's pen (UltraPen), however, is innovative in that it is both cordless and does not use any batteries. The UltraPen works by having the tablet emit periodical electromagnetic signals, which are detected by the antenna in the pen. These impulses are the pen's source of energy. The power received is used to send a signal back to the tablet. As the pen does not use any batteries, it is lighter and thinner, hence making it very comfortable to use. UltraPen is also pressure sensitive, making it ideal for drawing, painting and retouching. For example, line thickness can be varied by the application of pen pressure on the tablet.

The pen tip can also be used as the equivalent of the left mouse button and a second button on the side of the pen is equivalent to the right mouse button. The UltraPen has an improved version of its basic pen, call the UltraPen Eraser. The eraser tip can be used as an eraser or a second tool.

With the advent of pen-based notebooks PC's (slates) and PDAs, tablet technology is altering as an indirect method of input. In these systems, transparent tablets are integrated with a flat-panel LCD screen. Indeed, the defining hardware element of pen-based computers is the combined digitizing tablet and LCD.

Light pens are used in conjunction with a PC display monitor and controller. The light pen consists of an optical sensor in the tip of a pen, used to detect the electron beam of the CRT during the scanning process of the display. The sensor picks up the exact moment the electron beam passes under the pen and uses the controller to compute the position of the electron beam from timing circuitry connected to the display. Since light pens depend on the scanning of the CRT, their accuracy is that of one CRT pixel; in the case of VGA displays: 640 by 480 pixels. Pen Direct for Windows from FTG Data Systems is one of these systems.

The Pen Direct hardware consists of a controller box with a number of pass-through connectors for the keyboard and a CRT monitor. The light pen has a wire connecting in to the controller box. The CRT pass through tracks the display update and the position information is sent through the keyboard interface to the associated driver. The tip of the light pen is used like the left button of a mouse and two on-screen icons provide for additional mouse buttons.

Most pen-based systems today have ice-like surfaces to write on, making them harder than traditional pen on paper writing. In response, new writing surfaces are being produced with more friction, from vendors such as CalComp. Hardware vendors are also working to minimize the parallax seen between the writing pen and the digital ink produced on screen.

Pens have always enhanced our ability to draw and sketch, and the employment of this simple instrument has proved to be of great value in IT applications. Pens are also essential for the input of handwriting and are well suited to the application of handwriting gestures in computing. The next section describes the underlying technology in the fulfillment of the latter devices.

4.3.4.2 Handwriting Recognition Technology

The achievement in handwriting recognition has failed to meet expectation, to the extent that most users of early pen-based systems with handwriting recognition have become disenchanted. Like voice input, gestures and handwriting can be very critical of the way we work. With the current status of handwriting recognition technology, users have to work hard to get results. Users have to write in a way the handwriting recognition application requires. For example, Pen Extension for Windows require that handwriting be in the form of printed characters rather than in script. Graffiti (Byte Magazine, June 1995), another alternative, requires users to write in a simplified version of the English alphabet.

Effective handwriting recognition is difficult to implement but there are various strategies available to effect recognition. Generally speaking, current handwriting recognition technology employ one or several approaches to recognition including basic template matching, Hidden Markov Modeling (HMM), or neural networks paradigms (Byte Magazine, Oct. 1993). Handwriting style mandates a different approach to recognition, and there are basically two types that would dictate this, unconstrained and discrete. Unconstrained handwriting includes handwriting with a mixture of cursive (script) and printed characters whereas, discrete handwriting means neatly printed letters, each letter clearly separated by white space.

In the template matching method, the recognizer tries to match one of a set of basic patterns against the strokes to be recognized. These in turn are subdivided into a number of sub-alphabets, which are use to map the input to language specific alphabets during the recognition process. Unlike template matching, HMM put the variability in the model instead of the matching process. An HMM is created from as much handwriting data as possible, statistically modeling the variation seen in the data. An observed unknown character can then be compared to the HMM of a known character to get the likelihood that the unknown character is modeled by the HMM. Likelihoods of HMMs for different characters are compared to get the best match. The HMM method is best used in recognizing unconstrained cursive writing.

Back-propagation neural-network techniques enable a network to iteratively learn to recognize characters by adjusting the network's weighted connections using back-propagated errors. Longhand by Lexicus (Palo Alto, CA) employs this technique to considerable success in recognizing raw images and patterns in cursive handwriting. To improve on recognition rates, Longhand has a 25,000 word dictionary which it uses statistically in matching unrecognized words. When a word is unrecognized, a list of probable words is generated for the user to pick the intended word. Lexicus claims the process takes 1 or 2 seconds and that overall recognition exceeds 90 percent.

In line with the employment of dictionaries to handwriting recognition, grammatical and contextual analysis methods of trying to guess the likelihood of certain letters or words occurring near each other, based on language rules are being researched.

IBM is developing a discrete handwriting recognizer by combining elastic matching techniques with the employment of neural-networks (Byte Magazine, Oct. 1993). Elastic matching uses computational and statistical methods to spot deviations from the model characters. By measuring perhaps six or eight Fourier coefficients plotted between representative points on both the unknown and reference characters, an elastic matching algorithm calculates whether the coefficients fall within a permissible range. One study found the resulting error rate to be half that of non-elastic matching. During the recognition process, elastic matching works in parallel with neural-networks to obtain an output decision represented as a voting result. Because the technologies are complementary, the accuracy prior to training is substantially better than any known single-technology approach. User training further improves on the accuracy and has also been found to reduce on the number of computations during the recognition process.

Another approach is taken by Graffiti, a cross-platform recognition engine from

Palm Computing (Los Altos, CA). Graffiti requires users to write in a simplified version of the English alphabet adopted by the company, making each character more distinguishable and less confusing with others. All but six of the 26 letters are the same as their traditional uppercase and lowercase equivalents but the rest are generally based on parts of traditional characters. Recognition is reportedly close to 100%, and the company claims that most people become competent with the new alphabet in about 20 minutes.

The difficulty of implementing accurate handwriting recognition has also caused some vendors to promote digitized ink as a replacement for recognition. Digitized ink stores handwriting or any illustrations in a bitmap format, with additional data structure like stroke order and time stamp. A major disadvantage of the digital ink however, is the much higher storage requirement needed in comparison to ASCII text.

4.3.5 Touchscreen

Surprisingly, touch screens have been in existence since 1975. Touchscreens are commonly found in public information areas in the form of kiosks. They, however, are not confined to such domains, as they are also found in portable computing and are widely used in process control and monitoring.

The employment of touchscreen public information kiosks has the advantage of using the naturalness of pointing in humans, in the selection process. Selectable icons in touchscreens are also larger than icons found in other selection methods. This indirectly simplifies the screen for new and casual users, as information density is restricted. The drawbacks are, typically, added weight and power consumption, slower response times, and lower resolution, which makes touchscreens impractical for drawing applications. Touchscreens can also be tiresome to used for any extended period of time as the arm is typically outstretched during operation. The user's fingertip also obscures the display and sometimes have to pulled away in order that the user may read screen text and icons. And touchscreens are inadequate for sustained text entry.

Touchscreen systems generally consist of two major hardware components, a controller that manages the analog sensor and converts touch into digital information the computer can understand, and the sensors themselves, which are generally embedded in the touchscreen display. Currently, five sensor technologies are commonly found in touchscreens; they include capacitive sensors, strain gauge sensing, infrared sensors, resistive sensing and acoustic sensors. In the capacitive and strain gauges, the sensors are placed at each four corners of the display. Each of the sensors are able to detect the proximity of a touch with respect to itself. The sensors closest to the touchpoint report a proportionally higher value than those that are farther away. From readings from each value of the sensors, the controller is able to determine the x, y coordinate of the touch. The latter three sensors differ by having a row of transmitter and receiver sensors at opposite ends of each other in the vertical and horizontal directions. The touch point position is determined from scanning first in the vertical (y) or horizontal (x) directions for an increased reading in sensor value and then in the y or x direction respectively to determine the x, y coordinate of the touchpoint.

4.3.6 Voice Input Devices

Voice interfaces offers user the opportunity to use their most natural and best-developed communication skill in interacting with computers - speech. The promise of speech-recognition technology is that it will remove the communications barrier between people and machines. It will make computers accessible to everyone and will empower those who use it on a daily basis by making the interaction process more natural and effective.

Besides ease of expression, speech offers many other advantages in communicating with a computer. Speed being one of them, as most people easily speak at rates of 200 words per minute (wpm), yet few can type better than 60 wpm. Speech recognition systems can also provide for a hands-free and eyes-free interface, leaving them free for other work. Such systems would also provide for a very mobile computer, as no input keyboard is required. Dictation systems can also provide tremendous benefits to users whose language requires a laborious effort to input characters. For example, Apple's Chinese Dictation Kit (Byte Magazine, Mar. 1996) has shown input performance levels five times greater than in systems employing a Chinese keyboard. And not least, the potential of speech recognition systems can easily be seen to benefit people with disabilities.

Until recently, speech recognition has been largely confined to niche applications. However, a new generation of powerful speech-recognition technology is becoming commercially available in software that is low cost and that runs on standard PC hardware. Developers and vendors of speech recognition systems are continuing to improve their products by making them more accurate, faster and easier to use. However, current dictation systems still cannot handle unconstrained-dictionary, continuous speech, which is the natural manner of talking in human conversations. Today's voice-dictation systems require that users speak discrete words by having them speak carefully with pauses between each word. Typical maximum speeds obtainable from speech recognition systems today vary from about 60 to 70 wpm, with accuracy in the region of 90% and above. Dictionary size can vary from 5,000 words on entry-level systems to 30,000 or 60,000 words on larger systems.

As for the arrival of unconstrained continuous speech dictation systems, Neil Bernstein, North America marketing manager for IBM Voice Recognition predicts that such systems will be available before the year 2000. Such systems are already being prepared for specialist fields such as the legal and medical fields, with specific speech dictionaries. And judging from the trend in price drop of such systems, Venture Development predicts that by 1998 (Byte Magazine, Mar. 1996), dictation systems will cost less than £70. This, along with improvement in speech recognition speed and improved dictionary size will lead to extensive use of such voice systems in the coming years. Bill Gates believes that in 10 years, 95% of Web access will be voice driven (PC Magazine, June 1996).

4.3.6.1 Speech Recognition Hardware Technology

Speech processing is a sequence of transformations that converts an analog speech signal into its digital representation. It is essentially a signal-processing function. The minimal hardware required to support speech is a microphone and an ADC (A/D converter) chip. A DSP (digital signal processor) is not strictly required, but if used, it at least doubles the processing power for speech recognition. The microphone is used to convert changes in air pressure due to speech into its representational voltage variations. A system typically samples spoken input at 6kHz to 20kHz and then digitizes them using an A/D converter. The sequence of numbers thus created is called the digital waveform.

In principle, the raw signal from the microphone could be used directly in the recognition process. However, as these samples can be very large for each few second of utterances, and considering it contains both redundant information; processing it all would inefficient. Accordingly, digital-signal-processing (DSP) techniques are applied to reduce the redundancy and to enhance the salient features of speech. Common reduction techniques include filter banks and fast Fourier transforms. These techniques produce about 1000 to 2000 floating-point numbers per second of speech, about an order of magnitude reduction from the waveform. Essentially, no information is lost as the re-synthesization of digital waveform sounds nearly the same as the original speech. To gain further efficiency, at a small loss in accuracy, some systems use speech compression.

Standard PCs have been applying relatively inexpensive DSPs and dedicated processors that reside on expansion boards that can plug into system buses for speech recognition. More recently, dedicated speech recognition PCMCIA cards (PC Cards) are becoming widely available.

4.3.6.2 Speech Recognition Software Technology

Speech-recognition systems compare word utterances with pre-stored speech models, according to specified recognition algorithms and is also sometimes subjected to lexical and grammatical constraints. The recognition algorithm first converts the speech signal into a form that exposes its spectral content. This is then compared to acoustic word models to obtain a best match. No match will be exact, because slight differences in speed, tone and emphasis, and other details change a word's acoustic patterns and length, even with just a single speaker.

Different speech-recognition systems represent words in different ways. The three most common methods of representing speech models are through using templates, HMMs (Hidden Markov Models), and neural networks (Byte Magazine, Dec. 1995). Templates encode acoustic patterns from one or more samples and then compare acoustic patterns with spoken input, frame by frame. These templates represents a frequency time picture of words available in the speech recognition dictionary. To counteract the variation in spoken word speed, some speech-recognition software mathematically distort the time axis of each template until it best fit the unknown speech, a technique call Dynamic Time Warping, or DTW.

However, as a single template cannot describe the full variability of pronunciation, developers of speech recognition systems turned to putting the variability in the model instead of in the matching process, a technique call HMM. HMMs have superior generalization ability, and they have been found suitable for large vocabularies and continuous-speech, as well as speaker-independent, applications. HMMs are the predominant technology in most research systems and some commercial systems. Two recognition algorithms commonly used with HMMs are the Baum-Welch maximum likelihood ("best match") algorithm and the Viterbi ("best path") algorithm. Both process the input through an HMM and produce a probability rating. Each word in a speech recognition dictionary is modelled on the HMM from spoken samples of that word. Each state in the model contains acoustic information about a segment of the word, including acoustic variability. Transitions contain probabilities to determine the likelihood that one state will follow another state, leading on to the final probablistic word output.

Use of artificial neural networks has begun in commercial speech recognition systems. However, large scale of such systems have yet to appear as neural networks are still mainly used as components in research or commercial systems. Neural networks have the advantage of being able to extract complex patterns from large quantities of disordered data, making them good at generalization and hence speech recognition.

Speech recognition systems generally apply back-propagation neural networks in its recognition process. In simple terms, a back-propagation neural network learns to perform a task through an iterative, supervised learning procedure. The network typically consists of three or four layers of individual processing elements, also known as neurodes. Each neurode in a layer receives input signals from each neurode in the previous layer and transmits its single nonlinear output to all the neurodes in the following layer. The connections between the neurodes are individually weighted (both positively and negatively).

The network is trained by presenting the input layer with, in this case a spoken word data pattern. The activity in the input-layer transmits to the middle layer and then to the output layer, where the network's answer is compared to the true answer for that input pattern. In the event of an error, the result is propagated backward to the middle layer which generates changes to the weight values between the layers. This process repeats for each pattern in the training set. Eventually, the system learns the right answers for the input set and can be exposed to untrained data patterns. Training a back-propagation network can take from a few dozen passes through the entire training set to hundreds of thousands of passes for very complex problems.

With current technology, matching all sounds (phonemes) against the input provides unacceptably slow performance, so speech recognition systems take advantage of lexical constraints to consider only phoneme sequences that represent words. They also apply language constraints to ensure that they consider only legal word sequences (thus reducing the number of active words examined during speech recognition), or to bias the system toward more likely sentences. Evaluating the model and applying lexical and language constraints are typically combined into a one-step search process.

4.3.7 VR Input Devices

Virtual reality (VR) is very much a loose, and overused, term. On a simple level, the phrase can be used to describe any artificial world simulated by computer and this dates back to after the second world-war when the first flight simulator was developed by the U.S. Air Force (Jacobson, 1993). Whereas, a true virtual world today allows users to explore freely the VR environment in real time, and allows the user to interact and manipulate objects within it.

The popular perception of VR where a head mounted display (HMD) is worn is actually emersive VR. Computer-generated images are displayed on an independent pair of screens positioned just a few millimeters in front of each eye. Motion tracking devices in the headset track the movement of the head, normally across three axes - yaw (side to side), roll (tilt) and pitch (forward and back). This information is then relayed back to the computer which then updates the image accordingly, thus giving a strong impression of being immersed in the virtual environment.

4.3.7.1 Stationary Trackers

VR head trackers are used to determine the orientation of a users head. The information amassed is fed into a computer to generate or update the view of the user, on a HMD or a normal CRT display. The former device being the more popular and is the norm but the latter is a cheaper alternative and has its advantages. These devices are generally stationary trackers as users remain stagnant while using such a device, be it standing or seating. The tracking technologies commonly found in such devices include AC and DC magnetic fields, light (infrared) and sound (ultrasonic), gyroscopes and potentiometers. Navigation in the virtual world is facilitated by the use of a 3-D pointing device as described in Section 4.3.3 or data gloves that employ similar absolute positioning devices to the 3-D pointing devices mentioned.

StereoGraphics glasses which employs a CRT display as an output medium, incorporates the same ultrasonic tracking technology as Logitech's 3-D mouse. It has an ultrasonic transmitter affixed at the bridge of the glasses which a triangulation tracker mounted on a CRT display is able to track. Moving ones head to the right reveals more of the right side of the viewing object, moving it down, likewise reveals more of the bottom side of the object, etc. The triangulation tracker also supports absolute positioning of the head giving rise to subjects being able to move closer to viewing objects by the action of moving the head forward. This motion is still relative to the stagnant position of a subject as CRT displays are not able to follow a user's motions. HMDs however, can take full advantage of absolute positioning as the display is always in sight of the subject. The advantage of StereoGraphics glasses is that they are affordable and they provide better screen resolutions to any existing HMDs. A major drawback is that such devices have a very limited field of view.

Unlike StereoGraphic glasses, HMDs provide their users with the feeling of being totally immersed in the computer generated virtual world. There are fewer restrictions in head orientation as users are able to turn around in a 360 degree space on the yaw axis. The other two axes, pitch and roll, can work across plus and minus 45 degrees, depending on the design of the HMD. The orientational data collected on the viewing field of the subject is used to generate stereo images of the virtual world. More is discussed about the output aspects of HMDs in Section 4.4.1.1.

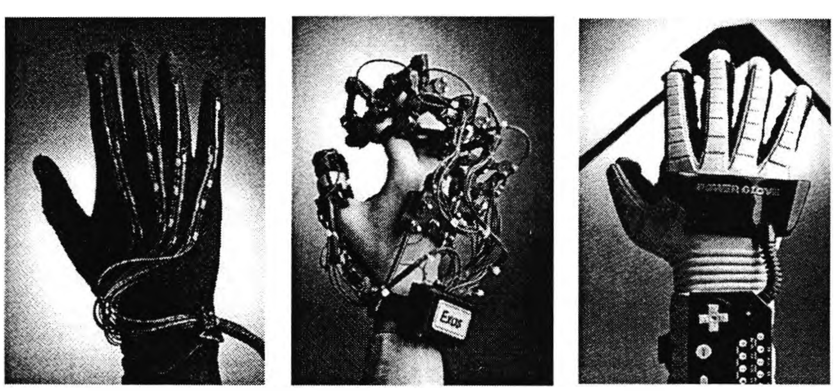
Activator is an infrared full body motion body sensor that could be used as a 3-D mouse input device or a body tracker. The input system is built with low cost plastic optics and a common micro-controller. It forms a flat octagon on the floor sending up a screen of infrared light beams surrounding the user. When a user breaks through the ring of lights, body motion can be simulated on screen. The Activator can also be used as a virtual musical instrument, whereupon breaking the light beam in certain places causes notes to be played.

4.3.7.2 Mobile Trackers

Mobile absolute positional trackers for HMDs are not very common but such systems do exist. An example of such a system is called the Optoelectronic system developed by University of North Carolina, Chapel Hill (Azuma, 1993). This system is one of the first scaleable tracking systems that can be extended to an arbitrary room size. The system employs ultrasonic technology in tracking a subject within the system. Optical sensors mounted on a HMD view panels of infrared beacons in the ceiling above the user. The known location of these sensors provide enough information to compute the position and orientation of the user's head. The system is able to resolve head motions of under 2mm in position and 0.2 degrees in orientation. And this is without distortions commonly found in magnetic trackers.

4.3.7.3 Hand Trackers and Navigational Systems

Hand trackings devices use various technologies to sense the position and orientation of the hand wearing it. They are commonly used with HMDs and are used as navigational systems within a virtual world as most HMDs are used as stationary trackers (Section 4.3.8.1). This section discusses three commercially available hand tracking devices - DataGlove by VPL Research, Inc., Dexterous Hand Master by Exos, Inc., and Power Glove by Mattel, Inc. (Figure 4.18), (Byte Magazine, 1990).



(a) DataGlove (b) Hand Master (c) Power Glove

Figure 4.18 Three commercial hand trackers

DataGlove was developed in the 1980s by T. Zimmerman and is perhaps the best known of the three. It makes use of fibre optics in determining hand configuration and magnetic field interference in locating hand position in three space. The DataGlove incorporates a network of fibre optic cables stretched along the back of a subjects fingers and hand. The technique relies on shining a light through one end of the cable and registering the dimming of light at the other end during the flexing of the fibre optic cables. Some of the fibres are etched at the finger and knuckle joints, which result in a loss of light when the fingers are flexed. As the light diminishes, the processor records more bend. In all there are 10 sensors for each glove, two for each finger. The computer uses this data to determine which joints were flexed and to what extent, and then adjusts the display accordingly.

In the navigation and orientation of the DataGlove in 3-D space, the glove incorporates a Polhemus 3Space Tracker that measures magnetic interference in 3-D space. The method is based on the physics that an electrically charged coil generates an electromagnetic field which is strong in the direction of the coil's radius and weak in perpendicular direction. The Tracker uses a transmitter and a receiver with three coils or wire, each perpendicular to each other. The Tracker controller pulses each of the transmitter's coil in turn and reads the current generated at each of the receiving coils. Based on knowledge that the strongest readings come from coils that lie on the same plane as the transmitter, the microprocessor can determine the orientation of the receiver in space, as well as the distance in the x, y, and z directions. The 3Space Tracker is accurate to $1/10^{th}$ of an inch (~ 2.5 mm) in the x, y and z position and to half a degree in orientation. The range of the Polhemus Tracker is 3 foot (~ 0.9m).

Dexterous Hand Master employs a different technique in determining the configuration of the hand. It involves an intricate lightweight aluminum exoskeleton of magnets and sensors that measure the bending angle of each joint in the hand. This attaches to the hand and fingers by means of Velcro bands. The sensor, built into the hinge assembly located at each finger joint, responds with a voltage proportional to the strength of the magnetic field. A small magnet bound to the sensor moves closer to or farther from it as the joint bends giving rise to positional feedback to the Hand Master controller. The Hand Master offers greater precision to the Data Glove but at a small trade-off in convenience. It uses the same Polhemus Tracker as the Data Glove in tracking the position and orientation of the hand.

For the gaming industry, Mattel has created the Power Glove for the Nintendo system. As the fibre optic cables used on the Data Glove are too delicate, Mattel has opted for flat plastic strain gauges for sensing finger configuration. A single sensor is used for each finger to measure all joints at once. This reduces hand configuration accuracy but is sufficient for the gaming industry. As the glove had to be affordable, the system employs an ultrasonic ranging system, similar to Logitech's 3-D mouse rather than the expensive Polhemus Tracker device. A small transducer at the back of the Power Glove sends out a short click to three receivers, one each to the top left, top right, and bottom right sensors attached to a display monitor. The absolute positional distance and orientation of the glove is determined from the time it takes each of the three sensors on the monitor to receive the transmitted clicks. The mathematical method of determination is based on a triangulation technique. The accuracy of the Power Glove to track hand movements is to within a quarter of an inch (~ 6mm) and has a range of five feet (~ 1.5m).

4.3.7.3.1 Gestures

Gestures are so much a part of human communication that we seldom notice them. With the employment of hand tracking devices, it is only natural that the use of hand gestures to convey information to a computer be utilized. CyberGlove (Figure 4.19), for example, a lightweight and flexible second generation interface glove employs neural network technology to recognize hand gestures (Cotton & Oliver, 1995). The advantage of using hand gestures is that it provides for a faster and more intuitive interface, while providing more functionality. For example, the action of pointing and dragging in an application is more natural with a finger than a mouse. The finger provides for a more direct method of input. Working in 3-D space is another, creation or manipulation of a 3-D object becomes more natural when users are able to manipulate them as they do in the real-world. Imagine being able to extrude a 2-D object by stretching it in a direction or rotating it like a real object to obtain a different view of it, the whole process becomes more intuitive as the actions correlate to those in our world.

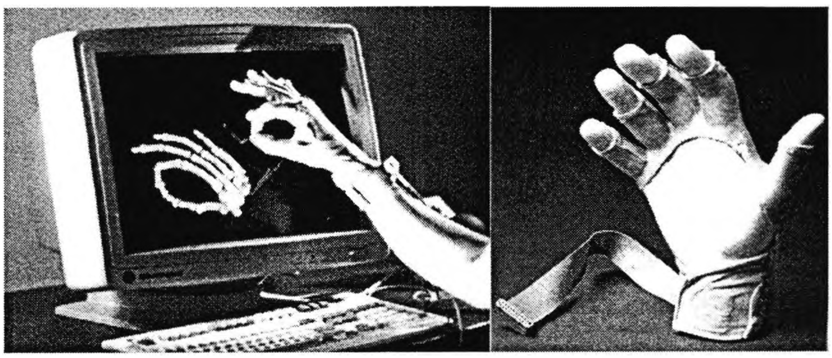


Figure 4.19 CyberGlove employs neural network technology in hand gesture recognition

4.3.7.4 Video Cameras

Hand trackers are not the only means of reading gestures. Another popular alternative is the video camera. The advantage of using a video camera stems from the fact that the input becomes non-intrusive and hence more natural without the constraints imposed by having to wear complex tracking devices. A research example that employs this method of input is VideoDesk (Krueger, 1983). VideoDesk works by having an overhead camera watch a user's hands over a desk. The image of the hands are projected onto a display facing the user while the computer watches for any gestural information. VideoDesk has been tested in telecommunications, whereby a teacher and student in different locations discuss a homework assignment. In this case, two colour coded hands are shown on the display, one belonging to the teacher and other the student. Instructions are based on gestures though in this situation the interpretation is human in origin. It has also been used in drawing, interacting with computer generated critters and the creation of 3-D solids where direct gestural information is interpreted by a computer.

Another area of research that is receiving more recent attention is the perception and interpretation of facial expressions. Neural networks are commonly used in the facial interpretation process. Collaborative work between University of California at San

Diego and Dartmouth College has trained a neural network to recognize facial expressions associated with specific emotions and to identify gender.

This research group captured the video images in a 512 x 512 pixel format. As this format was too large to be training data for the neural network, the video images where reduced to a 64 x 64 pixel format by averaging the relative gray-scale level in each pixel, normalizing the brightness and then passing them through a data-compression network. This data was then fed into a neural network with the same input and output format of 64 x 64 neurodes, but with a hidden layer that was significantly lower. The idea was to train the output layer to reproduce the input image after it has passed through the small hidden layer.

Once the hidden layer of the neural networks was able to reproduce the original images, the hidden layer was extracted as the input to a second two-layer network. This final network was then use to identify the emotion expressed by the person in the image. The completed neural network has shown good research results by being able to correctly identify most of the portrayed emotions, and where mistakes were made, they were usually debatable even amongst humans.

4.3.8 Devices Under Development

4.3.8.1 Eye-Gaze

Eye-gaze research has been going on since the late 1980s by R.J.K. Jacob in the HCI Lab at the Naval Research Laboratory (NRL), by J. Levine at IBM, T.E. Hutchinson at the University of Virginia and other laboratories throughout the world (Jacob, 1993).

The most widely used method of determining ocular point of regard is based on the "bright eye" phenomenon. The measurement is based on the vector distance between the glint and pupil center and, when calibrated, determines eye position on a computer display with high accuracy. The method applies infra-red illumination over the face of the monitoring subject through a light emitting diode placed at the center of a video camera lens. This produces a high signal-to-noise image of the eye's pupil. The captured video image is analyzed using image processing techniques on a computer, searching for the pupil center and the center of glint reflection arising from the front surface reflection of the infra-red source.

Besides the incorporation of an infra-red emitter into the lens of a camera, there is nothing new about the hardware technology of eye-gaze systems. Frame grabbers are widely available, and now, inexpensive video-conferencing digital cameras are beginning to appear in the market. This makes the commercial employment of eye-gaze technology feasible. The employment of this technology today, is not so much held back by the limitations of the hardware but on the methods of interaction using this new concept of eye-input. Thus far, the eye is classically considered as a information receiver or sensor, and the idea of the eye playing a part as an output medium is still in its early stages of development. More research needs to be poured into the employment of eye-gaze technology as an input device or just as a monitoring equipment. One area that have seen successful application of eye-tracking technology is in hand-held camcorders. The ES5000 camcorder by Canon for example, uses the technology to automatically focus on objects the viewer is looking at (CNN News).

4.3.8.2 Reading Your Mind

Use of brain signals in the control of machines has been researched using prototype telepathic controllers at the Nippon Telegraph & Telephone labs in Japan and at Stanford University in the U.S. The devices consists of a lycra head gear with mounted sensors similar to that used in an electroencephalograph (EEG) employed in the detection of brain waves. A neural-network is used for the interpretation of the brain waves detected. Before any interpretation can be made on the user's brain waves, the neural-network has to be trained on the specific word commands needed. Researchers have found that thoughts affect brain wave variation and it is in this variation that the researcher are trying to employ neural-networks in the recognition process.

The neural network is trained as the user concentrates on specific word commands. Each word command generates characteristic brain wave variations when concentrated upon. One or more neural networks are used to interpret the signals and translate them into controlling commands. In one prototype system, a user was asked to concentrate on the words left, right, up, and down. The neural network (usually a back-propagation network) learned to interpret the brain wave characteristics of each word, and it associated them with the appropriate control commands. The results of the experiment were encouraging as there were some positive feedback.

Ongoing research is now being carried out by British researchers, and in conjunction with a group of Austrian scientists. The research is to first benefit the disabled in controlling their wheelchairs, but is later hoped to be used to control computers and more sophisticated machinery. Four electrodes are placed on the subjects head, close to the motor cortex of the brain to monitor the brain waves characteristics used in motion control. Current brain wave characteristics from lifting the left and right index fingers, the tongue and toes are sufficiently distinguishable to function as up, down, left and right instructions. Presently, the four motions are detected accurately four out of five times. The research team hopes to have a trial device by the beginning of 1997.

Several problems must be overcome before this technology becomes part of any commercial product; ensuring the precise positioning of the sensors on the head, shortening the response time of the system, and avoiding the necessity of training the system for each user. Research on implanting an electronic chip directly into the human body will eliminate the first two problems. Academics and military scientists in Britain and America are researching methods of implanting electronic chips directly into the back of the neck (The Sunday Times, 16 Apr. '95). Such implants will allow users to communicate with machines/ computers through a tiny infrared transmitter and receiver, placed on the chip itself. Theoretical research on grafting such implants is being carried out by a team led by Prof. Greg Kovag (Stanford University, CA). Thus far, the team has learned how to fuse the chip with nerve endings and have extended the life of the chip from matter of days to over a year. One group has already stated that such implants might become a reality within a generation.

4.3.9 Comparisons of Input Devices

Experimental evaluations on various common input devices such as the keyboard, mouse, trackball, joystick, light pen, graphics tablet and touch screens have been conducted by various researchers (English et al., 1967; Card et al., 1978; Stammers et al., 1980; Albert, 1982; Haller at al., 1984; Karat et al., 1984; Pearson & Weiser, 1986; Murata et al., 1991). However, the evaluation results of these experiments do vary. For example, an earlier study indicates that the trackball is faster and more accurate than the joystick (Albert, 1982). Yet, a more recent study (Murata, 1991) demonstrated that the trackball was the slowest, and produced the largest error rates in comparison to all of the input devices investigated. The latter experiment included all the mentioned devices in this paragraph, but excluding the keyboard. Such, variations in experimental findings can normally be attributed to the nature of the tasks performed in each experiment.

In general, the mouse is often found to be fast, and with low error rates (English et al., 1967; Card et al., 1978; Murata, 1991). Studies also indicate that the light pen or touch screen, were among the fastest but the least accurate, especially the touch screen (Shneiderman, 1992). The speed of direct input devices, such as these, was often accrued to the directness of these input devices. While, their inaccuracies could often be attributed to problems of feedback, physical design, and interaction strategies used. There has also been research on comparing input devices to the keyboard cursor control. The general conclusion is that pointing devices are faster than keyboard controls (Shneiderman, 1992), but this result is very dependent on the task at hand. For example, for short distances, the keyboard cursor keys were often found to be quicker to using a pointing device. The result also depended on whether there were frequent shifts from keyboard to mouse and back during the performance of the task.

To aid the selection of an input device, the author has compiled a comparative table (Table 4.1), listing all the input devices covered in this chapter, along with their key features, drawbacks and task suitability. The task suitability covers the common tasks performed during a computer session (Foley et al., 1984). This includes selecting, positioning, orientating, path making (following/ creating curves), quantifying (numeric entry) and text input.

Table 4.1 Summary comparative of the various input devices covered in this chapter (continue…)

				Task Suitability					
Category	Device	Key Features	Drawbacks	Select	Pos^n	Orient	Path	Quan-tify	Text
Keyboard	Standard	Good for text and numeric entry. Many people are familiar with a keyboard. Up to 150 words per minute for the trained.	Slow for the untrained, less than 1 keystroke per second.	▒	▒			■	■
	Chord	Text and numeric entry. Very fast for the trained, up to 300 words per minute.	Requires considerable training.					■	■
Mice &	Mouse	Most common and popular pointing device. Two or three buttons, third button being programmable with latest models. Hand rest in a comfortable position. Precise positioning.	Consumes desk space. Mouse wire can be cumbersome, some are now cordless. Requires some practice (5 - 50minutes).	■	■	■	■		
	GyroPoint	Much like the common mouse when used in mouse mode. Ideal for presentations when used in the air.	Similar to the common mouse. Tiresome for the arms when used in air for extended periods of time.	■	■	■	■		
Other Pointing Devices	Trackball	Fast cursor motion. Does not require good grip for accurate use. Uses much less desk space than a mouse. Has programmable buttons.	Mouse buttons are easier to access than the buttons on a trackball.	■	■	■	■		
	PenMouse	Used like a pen. Uses less desk space than a mouse.	Has to be picked up like a pen, for each use.	■	■	■	■		
	TrackPoint	Requires no deskspace, built into keyboard. Requires less hand motion, from keyboard to mouse and back.	Less accurate to a mouse. Not suitable for complex drawings.	■	■	■	▒		
	KeyMouse	Requires no deskspace, built into keyboard. Requires less hand motion, from keyboard to mouse and back.	Less accurate to a mouse. Not suitable for complex drawings.	■	■	■	▒		
	TouchPads	Intuitive to use, replacing Trackball and Trackpoint devices on notebook computers.	Less accurate to a mouse. Not suitable for complex drawings.	■	■	■	▒		

Table 4.1 Summary comparative of the various input devices covered in this chapter (continued)

Category	Device	Key Features	Drawbacks	Task Suitability					
				Select	Pos^n	Orient	Path	Quan-tify	Text
Other Pointing Devices (Cont.)	FeetMouse	Leaves hands free. Suitable for coarse movements.	Not suitable for drawing.	■	■	■			
	Joystick	Good for cursor positioning. Some joysticks have high precision control. Excellent for tracking due to ease of direction change.	Requires high levels of concentrations. Not suitable for drawing due to awkward motion to drawing correspondence.	■	■	■	■		
3-D Input Devices	RingMouse	Hands does not have to leave the keyboard during cursor motion. Supports 3-D cursor movement. Can emulate a joystick.	Does not provide precise control. Requires steady hands.	■	■	▒			
	Alps	Superior for 3-D input than the common mouse. Provides 6 degrees of freedom. Provides precision control.	Can cause arm fatigue in prolonged use.	■	■	■	?		
	Logitech	Superior for 3-D input than the common mouse. Provides 6 degrees of freedom.	Can cause arm fatigue in prolonged use.	■	■	■	?		
	SpaceBall	Superior for 3-D input than the common mouse. Provides 6 degrees of freedom. Has arm rest to support arm.	Less intuitive to the other three methods. Requires strong grip.	■	■	■	?		
Pens	Light Pen	Provides a direct (on-screen) and natural input method. Enables gesture and hand-writing recognition. Excellent for drawing.	Users have to pick the pen up to use it. Causes arm fatigue in prolonged use. Hand obscures screen.	■	■	■	■	■	■
	Graphics Tablet	Provides a natural input method. Enables gesture and hand-writing recognition. Excellent for drawing.	Users have to pick the pen up to use it. Requires large desk space.	■	■	■	■	■	■

Table 4.1 Summary comparative of the various input devices covered in this chapter (continued)

Category	Device	Key Features	Drawbacks	Task Suitability: Select	Pos^n	Orient	Path	Quan-tify	Text
Touch Screens	Touch Screen	Provides a direct and natural input method. Robust.	Can cause arm fatigue in prolonged use. Requires frequent cleaning.	■	■	■	■	■	■
Voice	Isolated word recognition	Near natural input method.	Limited vocabulary. Requires pauses between words and training.	■	▒	▒		■	■
	Continuous speech recognition	Natural input method.	Limited vocabulary. Requires pauses between words and training.	■	▒	▒		■	■
	Speaker dependent	Higher accuracy than speaker independent systems and easier to implement, due to higher accuracy rate.	Dependent on speaker. User required to spend considerable time training the voice recognition system.	■	▒	▒		■	■
	Speaker in-dependent	Less training required. Speaker independent.	More prone to errors than speaker dependent systems.	■	▒	▒		■	■
VR Devices	Stereo-Graphic glasses	View objects in 3-D. Cheap.	Can cause eye fatigue or sickness in prolonged use.			■			
	Head Mounted Displays	Allows total visual immersion in a 3-D computer generated world. Affordable.	Can cause eye fatigue or sickness in prolonged use.			■			
Station-ary Trackers.	Activator	Allows the detection of body parts crossing a cylindrical space. Cheap.	Non-precise input method.	?	?	?			
VR Hand Trackers	DataGlove	Direct method of input. Could employ gestural input. Effective in manipulating 3-D objects. High hand tracking precision. Virtual keyboard for text and numeric entry.	Fibre optic cables are fragile. Less robust to the other two hand tracking devices. No tactile or force feedback. Expensive.	■	■	■	?	▒	▒

Table 4.1 Summary comparative of the various input devices covered in this chapter (continued)

Category	Device	Key Features	Drawbacks	Task Suitability					
				Select	Pos^n	Orient	Path	Quan-tify	Text
VR Hand Trackers (Cont.)	Hand Master	Direct method of input. Could employ gestural input. Effective in manipulating 3-D objects. Offers greater hand configuration precision. Hand tracking in 3-D space is equal to the DataGlove. Virtual keyboard for text and numeric entry.	Difficult to put wear and cumbersome to use. No tactile or force feedback. Expensive.	■	■	■	?	▒	▒
	Power Glove	Direct method of input. Could employ gestural input. Effective in manipulating 3-D objects. Virtual keyboard for text and numeric entry. Cheap.	Reduced hand configuration accuracy. Reduced hand tracking accuracy. No tactile or force feedback.	■	■	■	?	▒	▒
	Cyber-Glove	Direct method of input. Lightweight and flexible. Second generation interface glove. Uses neural networks for gesture recognition. Effective in manipulating 3-D objects.	Expensive.	■	■	■	?	▒	▒
	Video	Non-intrusive hand gestural input method. Facial expression recognition.	Additional processing power required to understand captured images. 2-D hand gestural information only.	■	■	■	?		
New Technolo-gy	Eye-gaze input device	Eye-gaze as an input method.	Undergoing usage research. User's head has to be still. Expensive.	▒	▒	?	?	?	?
	Mind Reading	Computer-mind control.	Undergoing research. Electrodes have to be placed on the user's head. Not available.	▒	?	▒	?	?	?

4.4 Output Devices

4.4.1 Displays

The computer display, as described earlier in the chapter, is the most common of all output devices used on computers of yesterday, today and into tomorrow.

4.4.1.1 Common Desktop/ Notebook Displays

Computer graphic adapters and displays have come along way since the first color graphics standard, CGA (Colour Graphic Adapter), was released for the IBM PC. CGA could support a maximum resolution of 640 by 200 pixels in monochrome or 320 by 200 pixels with four colours. Today, every major display manufacturer uses SVGA (Super Video Graphic Adapter) as its standard colour display adapter. SVGA adapters are able to support a maximum resolution of 1024x768 pixels with 256 colours or resolution of 800x600 pixels with 64,000 colours. The jump spans two generation of video adapters, EGA (Enhanced Video Adapter) and VGA (Video Graphic Adapter). Desktop monitor size has grown through the years too, with 12" monitors being shipped since the days of the CGAs, 14" since EGAs and recently the 15" with SVGAs. Larger monitor sizes are also available at 17" and 21". Gateway 2000 have gone a stage further by providing a 31" VGA monitor in it's latest "Destination" multimedia computer and home theatre high-end systems.

With notebook computers, VGA (640x460 pixels) monochrome LCD displays with 64 grey scales are already beginning to be phased out with the current passive matrix VGA screens with 256 colours or active matrix SVGA screens with 64,000 colours. Colour notebook computers typically have screen sizes of 10.4", with better machines having sizes that go up to 11.3" or 12.1".

4.4.1.2 Head Mounted Displays

Screen sizes has not just been growing larger, they have also shrunk for head mounted displays (HMDs) typically found in VR technology and soon to be seen in "wearable" computers. See Section 4.5.1 for further discussion. Screen resolution for such displays are still currently much lower than the current SVGA standard of 800x600 pixels. Affordable VR HMDs are already commercially available, ranging from headsets down to eye-glasses as shown in Figure 4.20 (CD-ROM Magazine, 1995). HMD has also made it possible for stereo images, which is important to humans in judging distance and interacting with their environment. This is achieved in a HMD with two independently generated images, offset to match the inter-pupillary separation of the human eyes, each visible only to the appropriate eye.

(a) VFx1 by Forte Technologies, Inc.

(b) I-glasses by Virtual i-O

Figure 4.20 Two commercially available VR HMDs

As for the non-VR user, the alternative is a tiny screen by Reflection Technology call the Private Eye, that attaches to headgear and hangs a few centimeters in front of the eye, creating the illusion of a computer screen floating in front of the user. The Private Eye works with one eye, the focal point being adjustable so that a user is able to focus on an external work or object while still viewing the floating screen. This allows users to carry out two tasks simultaneously, like referencing a technical document while performing repairs to a computer.

4.4.1.3 3-D Displays

Essentially, 3-D displays can fit into one or more of three broad categories: holographic, multi-planar, or stereo pair (Byte Magazine, May 1992). In general, the holographic and multi-planar displays produce the best 3-D images as the physiological depth cues are consistent. Additionally, these displays do not require special viewing devices as does the stereo pair. Holographic display is the most capable but the technology has yet to permit interactive manipulation of computer-generated images, thus making for a non-commercially viable solution to computer displays. Multiplanar and stereo displays however, have their limitations, but are commercial realities.

The underlying technology of a multiplanar display is based on using a rotating mirror to deflect the drawing beams of a CRT or laser in building a volumetric image. Volume is achieved through plotting points on the image at each plane to build up the volumetric image. Omniview by Texas Instruments (TX, US) is an example of such a multiplanar display. It uses a double-helix transparent display cylinder that rotates at 600 rpm, creating a cylindrical volume where 2-D images are fused by the eye to form a 3-D image. The disadvantage of a multiplanar display is the transparency of the image produced, which can cause confusion when looking at a complex 3-D image.

Generally, stereo pair technologies are the least expensive and most widely available. In its most basic form, stereo images can be achieved using red-and-blue filtered glasses. This method is restricted to monochramatic images as the technique is based on colour filtration. Another method based on using polarizing glasses, removes this colour restriction by polarizing the left image in one direction (say, vertically), while polarizing the right image in the other (horizontal). The former method is known as the time-parallel system as both eye views simultaneously while the polarization method is known as the time-multiplexed system as each eye view an image in sequence.

A common example of the time-parallel system is the HMD often used as part of a VR system. HMDs consists of two monitors, each offset to match the interpupillary separation of the human eyes. This, like the red-and-blue filtered glasses has the effect of producing stereo 3-D views. StereoGraphic's (CA, US) stereoscopic glasses is a leading example employing the time-multiplexed system to produce stereo 3-D images. The system involves switching the screen image between the left and right views at a frequency of 60Hz for each eye, synchronized with LCD "shutters" in the glasses. Synchronization is affected through infra-red transmission between a unit that sits on the viewing display and the stereoscopic glasses. When the left eye image is visible on the screen, the right lens is opaque; and when the right eye image is visible, the left lens is opaque. The brain fuses the left and right images to produce a stereo view.

4.4.1.4 Developing Display Technology

A recent development could bring high definition images to all types of display, ranging from televisions, camcorders, computers, cinema screens, VR head mounted displays, etc., within the next few years. The developed coating "remixes" light so that the eye is not able to see the black area currently seen to surround pixels on a display (Sunday Times, Sept. 1995). The removal of such, will produce images that are comparable to systems costing tens of thousands of dollars, currently being used by Nasa's space shuttle program. The new technology is cheap, and plans for mass production of this new coating called Microsharp should have already begun, as of late 1995.

Dimensional Media Associates (NY, CA) has developed a new 3-D display unlike those described in Section 4.4.1.2, as the projected 3-D image appears solid and suspended in the air. The system is called the High Definition Volumetric Display (HDVD). This technology accepts 2-D images from a variety of light sources, such as PC displays, and project them. The resulting 3-D aerial images can be up to 20 feet in width, and can viewed under a variety of lighting conditions. HDVD is able to project both stationary images and full-motion video. Additionally, by generating the images in a special format, a PC has the ability to act as a source of true 3-D images that can be viewed at different angles.

Another display system that is still under development, is a device that writes images directly to the human retina. In effect, the human visual system becomes part of the display. There are two main advantages to this system. Firstly, the image size is not confined to a fixed size, as would a typical computer monitor. Secondly, the display system does not require a physical screen, therefore, making a very portable display system.

4.4.2 Sound Output Devices

4.4.2.1 Stereo Sound

The original IBM PC's sound capabilities were practically nonexistent, they consisted a simple beeper that could produce a limited range of square-wave tones. Today, with the advent of multimedia, nearly all PCs come with a sound board capable of matching the 16-bit quality of audio CDs. Sound is the second most effective human sense, after sight. With computers, audio brings us one step closer to a realistic environment. It is especially true when one talks about games programming. However, sound is also capable of enhancing our everyday interaction with computers, by providing audio as an information feedback.

This point is illustrated very well in 'SonicFinder', an interface that uses auditory icons (Gaver, 1989). SonicFinder is a prototype of the 'Macintosh Finder' which uses a sonic vocabulary to provide audible feedback to users. For example, one can "tap" on an object in the Macintosh OS to determine it's size, small objects have high-pitched sounds while large objects are low pitched. These audio feedbacks provide a functional basis by reducing errors in our interaction with computers.

4.4.2.2 3D-Sound

Immersive 3-D sound, such as "Dolby Surround" and "QSound" are breaking new grounds in the audio computing industry (CD-ROM Magazine, 1995). The next generation of computer games and VR applications will be the first to exploit such a technology. This technology provides applications with a more enveloping, 3-D experience and enhances the effects of a computer generated 3-D environment.

4.4.2.2.1 Dolby Surround Sound

Dolby Surround was invented in the mid 1970s and was first exploited by the movie industry in films such as Star Wars and Jaws. Dolby Pro-Logic brings 3-D stereo sound into our domestic environment by allowing us to plug such a system directly into our stereo system, television, video recorder and lately, our computer. The system works by surrounding the listener with five speakers from four output channels. The left, centre and right speakers each use a channel, while the two rear speakers share the fourth channel. Dolby ProLogic systems will only produce Dolby Surround sound with a Dolby encoded signal. These signals isolates and redirects out-of-phase signals to the additional speakers, causing the full effects of 3-D sound to be experienced. Dolby encoded sounds are generally pre-encoded for playback but real-time systems are becoming available for interactive systems. The disadvantage of real-time systems are their substantial burden on the computer's processor. To overcome this problem, software developers are looking at software technology call QSound.

4.4.2.2.2 QSound

QSound is a software alternative to using systems like the Dolby Pro-Logic to reproduce immersive 3-D sound. Advantages of QSound over Dolby Pro-Logic systems include greater accessibility, as more users would have PCs with sound boards and speakers than Pro-Logic systems, and QSound also places less overhead on the PC's processor than Pro-Logic systems. Unlike Dolby Pro-Logic systems, however, QSound does not provide full 3-D audio but delivers a 220° sound field from two speakers placed in front of the user. QSound is a product of a three year research which includes 500,000 experiments conducted with people listening to a selection of audio effects played at different frequencies. A reference map was built up from the experimental data to determine the spatial location where the average set of human ears could detect a particular frequency. This data was then used to simulate sounds heard from locations beyond the speakers themselves by rapidly changing the frequency and volume of the audio signals.

4.4.2.3 Computer Voice Synthesis

A braille device is often used by the blind to read textual information off a computer screen. However, with the advent of GUIs, such devices are relatively ineffectual. To remedy this, voice synthesis has been used since the late 1980s to aid the blind in using some of the common GUIs of today. With so called screen-reader systems (SRD), disabled users can maneuver a mouse over a GUI element, like an icon or text, and a voice synthesizer describes the object pointed to verbally. Such systems are not only beneficial to the deaf, as they have potential in such areas as fax to speech, telephone voicing of dynamic databases, contextual spoken words instead of pre-recorded playbacks and in the provision of verbal output from computer agents (Section 4.2.7).

4.4.2.3.1 Voice Synthesis Hardware

Typical voice synthesis systems consists of either an add-in circuit board or a external serial/ parallel interface voice box and the appropriate text-to-speech software. The hardware synthesizer typically contains a DSP chip or D/A converter to help in the sheer number crunching requirements of recreating complex waveforms that make up human speech. Examples of such hardware synthesizers include DECtalk by Digital Equipment Corp. (DEC) which is a high-end internal speech synthesizer and Echo PC by Street Electronics Corp. The DECtalk PC can speak at a rate of 120 to 550 words per minute and contains more than 1400 letter-to-sound rules. Machintosh computers have their own pre-built hardware and software (MacInTalk) to allow for speech synthesis, and is one of the first platforms to achieve this feat.

4.4.2.3.2 Voice Synthesis Software

Most speech synthesis software is based on a three tiered approach developed by Dennis Klatt at MIT. The first tier is the text normalizer, used in converting the printed word into spoken form. For example, "£20.00" will be converted into "Twenty pounds sterling" instead of "Pound twenty point zero zero." Next in tier, a lexicon parser is used to strip any suffix and prefix a word might have. This is done to determine the root word so that it can easily be found in a text-to-phoneme dictionary. A phoneme is the smallest sound in a language, and the English Language contains about forty. The last tier is the intonation controller to provide for a more realistic pronunciation. This module is responsible for managing word and sentence pauses and pitch. Eloquence (PC Pro, Oct. '96) is an example of a text-to-speech developers toolkit, which translates English text into realistically human sounding speech.

4.4.3 Tactile and Force Feedback Devices

4.4.3.1 Tactile Feedback

Tactile feedback is important in our daily interaction with our surrounding, it provides us with a sense of continuum. When we come into contact with a surface, we feel the presence of an object. When we slide our fingers across the object, we get an idea of the texture of the surface. Through the sense of touch, we can estimate the size of the object and we also know where the object ends and another begins. One approach of achieving tactile feedback from a virtual object is through the use of shape memory metals. Such alloys return to their original form when heated. Xtensory employs this technique of tactile feedback on it's Xtensor tactile data gloves, see Figure 4.21. When the Xtensor data glove comes in contact with a virtual object, it sends an electrical current to the tactor, which then causes the metal strip to return to its original shape (Cotton & Oliver, 1995). This in turn applies pressure to the fingertip.

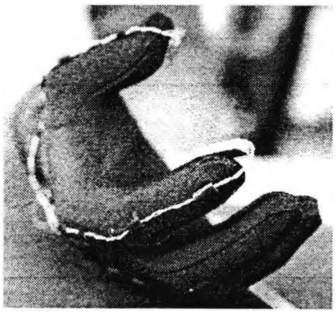


Figure 4.21 Xtensor tactile feedback glove by Xtensory, Inc.

4.4.3.2 Force Feedback

Force feedback is essential in providing the sensation of grasping an object. It is not enough to provide tactile feedback in these circumstances as we could be 'squeezing' an object without feeling it. To provide for a realistic grasp, refraining forces need be applied and this is currently being achieved through the use of an exoskeleton. For example, Sensing And Force reflecting exoskeleton (SAFire) by Exos, Ltd., provides joint torque feedback to human fingers using an exoskeleton as shown in Figure 4.22 (Cotton & Oliver, 1995). In grasping a virtual object, the exoskeleton would stiffen, becoming completely rigid in the case of a hard object, or springy in the case of a malleable one.

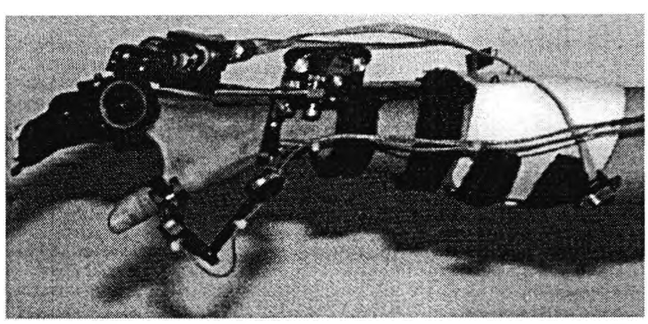


Figure 4.22 Sensing And Force reflecting exoskeleton (SAFire) by Exos, Ltd.

4.4.4 Developments in I/O Devices

Looking at the I/O trends, a new breed of human-computer interaction is emerging from eye-gaze trackers and some VR devices. These devices are based on a non-command style of interaction. The new method of input represents less intentional actuation of a device or issuing of a command, and is more like passive monitoring of the user. The trend is also towards a more natural form of working with computers. This includes the use of three dimensional trackers for 3-D work and navigation in 3-D space, video cameras and hand trackers in gesture recognition, pen in handwriting recognition and gestures, eye-gaze trackers and even physiological monitors in responding to user observations, etc. These are also being accompanied by output devices that provide force feedback, non-speech audio and head mounted displays.

The current trend in computing hardware is downsizing and improving the naturalness of how we interface with computers. The trend is now towards computers that one can wear or carry in a pocket, instead of one which fits on a desk or lap. Recent years has also realized enhancement or expansion of the modes of communication between humans and computers. I/O devices are becoming more natural and they are also employing more of our senses; sight, sound, touch and of late, smell. The latter is sometimes found in VR based applications, but is still very limited due to the problem of clearing and introducing them.

The ongoing I/O research is bringing fresh ideas to the study of human-machine interaction and these may be rapidly exploited, commercially. For example, British scientists are currently working on a new technology that will harness brain signals to power machines. A trial device is hoped to be developed in early 1997 to aid the disabled. This is discussed in more detail in Section 4.3.8.2. Another input device that has received considerable attention is the eye-gaze computer interface. Eye trackers have existed in laboratories for many years, but their development for commercial use is still under investigation. Further coverage on this is given in Section 4.3.8.1.

The drawback with these devices is that they require intensive processing power to enable real-time tracking or monitoring. In addition, the processor has to generate the user interface, respond to user commands and any other internal processes. However, with the advent of more powerful CPUs, like the Pentium and PowerPC chips, previously intensive based applications, like speech recognition, can now be done in real-time. Likewise, this trend will be seen with other currently non-viable devices.

The ultimate interface to a computer is not to have an interface at all. Such systems may be available in the not too distant future. Ian Pierson of BT Labs predicts that chips that directly interface with the brain will be available in 30 to 35 years. With a direct link to the brain, all we have to do is think about a problem and the chip will produce a solution. Another electronic implant for humans, the size of a rice grain, is currently undergoing research at the Illinois Institute of Technology, Chicago (New Strait Times, Apr. 1996). The device can be remotely triggered to deliver a small electric shock that can activate muscles, and is meant to assist paralyzed patients recover the use of their limbs. The system will work like a miniature cellular-phone network system, where a central controller (computer) will be able to transmit messages to a disabled limb carrying such electronic devices to activate them. The system is either, expected to be voice controlled or if technology permits, thought controlled (see Section 4.3.8.2). The research, however, may take another 10 years before being offered to the public. Similar research to the Americans is also being conducted at the University College of London.

4.4.4.1 Wearable Computers

Similarly, downsizing of computers and their peripherals is seen throughout this chapter. The use of wearable computer gears can be seen in the development of some recent technologies. For example, the Private Eye display by Reflection Technology (Section 4.4.1.1) and the hand-held Twiddler keyboard/mouse (Section 4.3.1.2) could be used with existing notebook computers in say a well padded back-pack to provide for a truly portable computer. Such systems could be used in difficult and tight environments where a notebook computer would not be possible. Better still, voice input technology could be incorporated into the system to provide for hands free operation. This is also currently available for existing notebook computers through IBM's PCMCIA VoiceType voice recognition system among others. Remove the screen and keyboard from the notebook computer, and place every other component into a smaller shell and we have a more wearable computer system.

In fact, such systems are already being researched at the Massachusetts Institute of Technology (MIT) in the US and British Telecom (B.T.) in the UK. A wearable computer has been commercially available for quite some time and is being used by ADT Automotive to book 500,000 cars a year into auctions in the US. Compuspeak uses a radio microphone and voice recognition as its input device. It had a voice dictionary of 100 - 200 words in late 1994, but this figure could have increased with today's technology, allowing for a wider application rather than dedicated ones in those days. It is claimed that 30% to 50% increases in efficiency can be achieved using Codeway, an American system for car booking (Sunday Times, Sept. 1994).

In the UK, British Telecoms has manufactured a prototype voice activated computer that one wears on the arm (Personal Computer World, Mar. 1996). The wrist band system has a touchpad and miniature colour screen that allows real time video conferencing, while a visor or HMD puts a larger display in front of one eye.

CPSI (US) has an available system which fits a 486-based 50-MHz computer complete with a 540-MB hard drive, dual PCMCIA slots, 16 MB of RAM, mouse, and voice recognition facilities that weighs about 3 pounds and is the size of a lunch box (Figure 4.23(a)). CPSI has incorporated Kopin's (Taunton, MA) state-of-the-art monochrome head-mounted display with VGA resolution and weighing only 6 ounces. The system uses lithium ion batteries that will support the whole system continuously for 6 to 8 hours. The current drawback of the system is it's substantial cost. Figure 4.23(b) illustrates a design prototypes by NEC, in it's wearable PC range, call Porto Office. The unit is worn like a backpack. It has a keyboard and screen display at wrist level with a speaker and earphones at the head. Figure 4.23(c) depicts a VuMan wearable computer from Carnegie-Mellon Engineering Design Research Centre. VuMan employs a "Private Eye" (Section 4.4.1.1) heads up display for output and a finger-pad or speech recognition as input to the computer.

(a) CPSI's Body-Worn Computer (b) NEC's Porto Office Prototype (c) Carnegie-Mellon's VuMan

Figure 4.23 Wearable computer system from various sources

Power consumption and battery life in portable systems are always an issue. Lithium ion rechargeable batteries are the latest to be supplied with portable computers, providing up to 6 hours of life. Zinc-air batteries could be next in line as they can provide battery life of up to 12 hours on a single charge. The weight problem with zinc-air batteries has recently been overcomed, but the issue of the low number of recharge cycles is not resolved. MIT however, has taken a different approach of extending the use time of their wearable computers by having their batteries recharged from the mechanical energy of walking through the heel of a shoe (PC Pro Magazine, Sept. 1996).

4.5 Conclusion

The current goal of research and developments in I/O devices is to increase the human-machine interaction bandwidth in media and styles that are well matched to and driven by human capabilities. This trend is to improve usability, and if continued, should bring about further improvements towards seamless interaction between humans and machines.

This chapter has covered a wide range of input and output devices. However, even after the numerous experiments by various researchers on some of the more common input devices (keyboard, mouse, trackball, joystick, light pen, graphics tablet and touch screens), there are still no hard and fast rules about which of these input devices are best (fastest, most accurate and usable). The results on these input devices have generally resulted in contradiction between the researches. Such contradictions, however, could be due to the nature of the empirical task performed, which can be quite different. Currently, there are no definitive research findings stating which of the input devices are best for an application. Definitive input and output devices can only come from testing them in the context of the task they are to perform. Interface design, interaction style and physical layout should also be a consideration factor in determining the appropriate input devices to employ. To assist designers in the initial stages of selecting an input device, Table 4.1 in Section 4.3.9 provides a complete summary listing.

As for the future in input devices, there might not be one. Instead, humans could have an electronic chip implant that allows them to communicate with machines. It is suggested that this might become a reality within a generation. Using brain activity to communicate with a machine would be the ultimate form of seamless interaction. If this is achieved, even output could be stimulated by the electronic implant. With signals sent to the brain, sight, smell, touch, taste, sound and even emotion can be communicated.

The next three chapters concentrate on the final tier of the pyramid, the 'look' of an interface, starting with the subject of colour.

5. Use of Colour

5.1 Introduction

The previous chapter discussed the 'feel' of an application, which is dictated by the input and output devices employed. The objective of this chapter is to study the effects of colour in HMI design, which is the first chapter covering the 'look' of an application. This chapter provides guidelines on effective colour usage, but more specifically, in the development of effective Human Machine Interfaces (HMI). It starts by discussing the desirability of colour in computer-based applications and then goes on to cover the basic properties of colour so as to allow the non-specialist to understand both colour and human perception. The chapter includes a section on the limitations of computer screens to display colour and also describes some of the properties and limitations of the human visual system in seeing colour. Following this, a compilation of guidelines is provided to aid designers in designing with colour. The chapter ends by providing a discussion on how these guidelines can be implemented effectively in the GUI design process.

5.2 Importance of Colour

Colour usage without the knowledge of the effects of them on users can be very destructive to the usability of the computer application. Introduction of meaningless colour in an experiment (Krebs & Wolf, 1979), reduced user performance to about one-third of what it was without colour. Similar findings of reduced user performance were also found by other researchers (Christ & Teichner, 1973 and Christ, 1975). The effective use of colour is not an easy matter as it draws from many disciplines including art, physics, psychology and physiology. This chapter brings together a collection of guidelines that have proved effective in its usage from various disciplines.

Many applications have no inherent need for colour, for example word-processors, software development tools and spreadsheets. Research has found no evidence that colour, as compared to black and white, can significantly improve aesthetics or legibility or reduce eye strain (Pastoor, 1990). So why use colour if there is no need for it? Imagine having two versions of a same map, one in colour and the other in black and white - preferably something with dense information content, for example the London underground map. The black and white London underground map in this case is adequate but the equivalent map in colour does make it easier for the user to interpret the information required and hence respond faster to the material. This philosophy applies directly to computer-based applications. Research by various researchers (Luria & Strauss, 1975, Christ, 1975 and Carter, 1982) has shown that, in dense screens, it takes fewer eye scans to locate objects correctly coded in colour than those coded by other methods. Other positive research findings of colour include improved performance (Kopala, 1981 and Sidorsky, 1982), effective organisation of information (Engel, 1980) and in aiding memory (Marcus, 1986b).

The wide spread proliferation of colour displays in industry, business and homes is largely due to cost reduction and advancements in display technology. This increase has led to constant pressure being placed on software designers to create their applications in colour because they sell better in comparison to their monochromatic equivalent. In the early 1990's, over 85% of display systems sold, were in colour. Today, this statistic should approach close to at least 90%. Since, practically every computer application will be viewed in colour, it is imperative to establish some guideline to its effective use. There are four basic ways colour can aid in communication; to identify, to inform, to please and to depict.

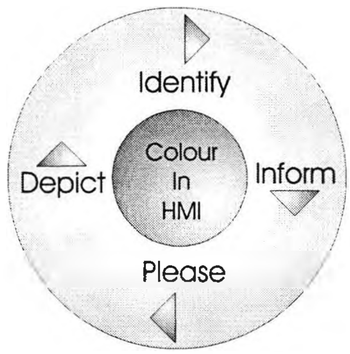


Figure 5.1 Using Colour in HMI Communication

5.2.1 Using Colour to Identify

Colour coding enhances the means of identification. Colour coding allows us to group objects of similar features together in a single scene or over multiple scenes. It is a means of differentiating or partitioning an object from its surroundings.

A good example of the use of colour to identify can be seen in Borland's C++ Integrated Development Environment (Version 3.1). It uses customisable colour coding known as "colour syntax highlighting" to assign different colours to comments, keywords and identifiers. This makes it easier to scan, read and catch errors in code editing.

Colours in our everyday life could be used to aid colour coding in computer applications. For example computerised maps could use the colour coding of nature in its representation of land and sea - blue representing water, yellow/brown representing deserts and green representing forests. Leonardo da Vinci (Verity, 1980) equated colours to the ancient elements - he designated yellow as earth, red as fire, green as water, and blue as air.

5.2.2 Using Colour to Inform

Colour interfaces can provide the user with information not available otherwise, or it can redundantly reinforce information imparted through another medium, such as position and shape. A good example of the use of colour in our everyday life to impart information is the traffic light. Green informs us that it is safe to go, red informs us to stop and amber informs us to be cautious. In this case, position cues of the lights reinforces its information content. In general, colour is used redundantly with other visual cues to re-enforce the meaning of the information.

Colour could also be used to locate information on a quantitative scale. For example, gradation from green, through yellow, to orange, then brown gives us knowledge of the seasonal time of the year. Gradation from blue, through orange to red could be used to indicate increment in temperature. Research indicates that gradient colour schemes are found to be easier to read than colour-based schemes (Keates, 1962). Hue-based codes are mainly associated with quantitative rather than qualitative changes (Olson, 1981).

5.2.3 Using Colour to Please

Colours influence humans in many ways, they affect our biological, emotional, aesthetic and psychic responses (Birren, 1978), they can excite, disturb, unsettle and soothe. Colours, however, can have very different meanings to different people. It depends upon personal opinion, creed and culture and upon the context in which that colour is used. It is worth taking this into account when designing computer applications as much confusion could develop otherwise. Table 5.1 depicts some typical daily association of colours.

Table 5.1 Typical association of colour

Colour	Typical Associations
RED	An aggressive and loud colour. It is a dominant colour and a very good eye catcher. It's symbolic of: heat, violence, danger, anger, blood, passion, destruction, hell.
BLUE	A soothing and stable colour. It conveys a sense of coldness, depression, sadness, loneliness.
WHITE	A colour that is associated with purity, innocence, peace, truth.
BLACK	A colour that can incite a feeling of death, gloom, silence, emptiness, wickedness, horror.
YELLOW	A colour that symbolise richness, gold, gaiety, gaudiness, warmth, brilliance, alertness.
GREEN	GREEN is the colour of nature, life, relaxation, freshness, sympathy, faith, hope, peace.

5.2.4 *Using Colour to Depict*

Colour is essential in the realistic portrayal of objects or scenes from the real world. Colour is being used widely to depict objects from the real world in computer graphics, in simulations applications like flight simulators, and more recently, virtual reality. In the graphics art industry, much effort is made to ensure WYSIWYG (What You See Is What You Get). This makes sure that what is seen on the computer display is what is obtained on a hard copy, not only in terms of colour but also in term of the format of text and graphics. This allows graphic designers to actually see what will be obtained from a printout without actually developing one and is a great time saver.

5.3 Difficulties of Colour Design

There are various reasons why the use of colour in the design of computer applications is complicated. They are as covered in Sections 5.3.1-5.3.4.

5.3.1 *Colour Interact with its Environment*

The appearance of a colour depends on the colour in the environment that surrounds it. For example, a yellow square on white and on black (Figure 5.2). Yellow looks darker on the white background with an effect of delicate warmth, and on a black background, the yellow appears sharp, and brilliant. Even though the figure is printed in grey-scale, the effect of colour interaction is still discernible.

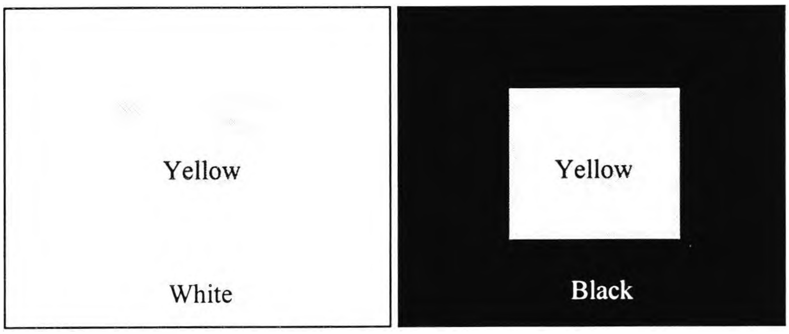


Figure 5.2 The effects of environment on perception of colour

Any colour is influenced by its location, its placement, and the size and shape of the area it fills. We cannot choose colours in isolation; they must be in context. Computer colour design also has a unique problem in that its display changes dynamically.

5.3.2 Changing and Variable External Lumination Affect Perception

Ambient light, be it daylight, fluorescent or tungsten, affects the appearance of colours. Reflections and glare spots are a source of visual distraction and reduce the contrast of images on the screen (Travis, 1991). In most working environments, light constantly changes through the course of the day due to the variation of illumination from windows and whether internal lights are on or off. This problem can be reduced by the use of well designed working environments.

5.3.3 Variation of Display Luminance Affect Perception

Most colour monitors today have brightness and contrast controls. This implies that users can, and usually do, have different settings on their displays. Variation of brightness on the affect of colours can be understood with the colour yellow. Under low brightness settings, yellow appears to be dim brown. At higher luminance, it appears yellow, and at even higher brightness levels appears white.

5.3.4 Physiological and Cultural Difference

The user population is made up of individuals with diverse colour perception capabilities. Age, colour deficiencies and cultural differences are factors that make up the almost impossible task of colour design. Greater coverage of this is included in later sections.

5.4 Properties of Colour

The following section covers the basic colour science, to prepare the reader for the descriptions that follow in the later sections. Colour can be described in terms of Hue, Saturation and Intensity. The colour sensations of an observer with normal colour vision ranges between approximately 380nm and 700nm in wavelength. The human sensitivity to this variation of wavelength in light is known as hue. An object, whether reflecting or emitting light, would more likely be that of a number of wavelengths (multichromatic) rather than a monochromatic light. Hence the sensation of a single hue is hardly encountered. Saturation is mostly related to the number of wavelengths contributing to a colour sensation. The narrower the band of wavelengths (e.g., 500 to 502nm) the greater the level of saturation. Similarly, the wider the wavelength band, the greater the extent of desaturation. A highly desaturated colour has a lot white in it, hence a desaturated red is pink and a desaturated blue is sky blue. Desaturation is the degree of whiteness in a colour. The intensity of a colour is directly related to its perceived brightness, i.e. the greater the intensity (or energy) of a light source the brighter the illuminated object appears.

5.4.1 HSI Colour Model

A colour model is a method for explaining the properties and behaviour of colour within some particular context. A widely used colour model is the HSI (Hue, Saturation and Intensity) model. A graphical description of the HIS model is given in Figure 5.3. Hue is measured from 0° to 360°. Blue is at 0°, red is at 120°, and green at 240°. Note that all the primary colours are at 120° separation from each other. Yellow appears at 180°. The vertical axis represents intensity measuring 0% percent from the base to 100% at the top of the axis. 0° is black regardless of the hue and saturation values, and hundred percent produces white. Saturation is represented by the radius of the colour model ring and is measured in percentages from 0% to 100%. It is a measure of the chroma or the amount of colour visible. The term chroma is used to refer collectively to the two properties describing the colour characteristics, saturation and hue.

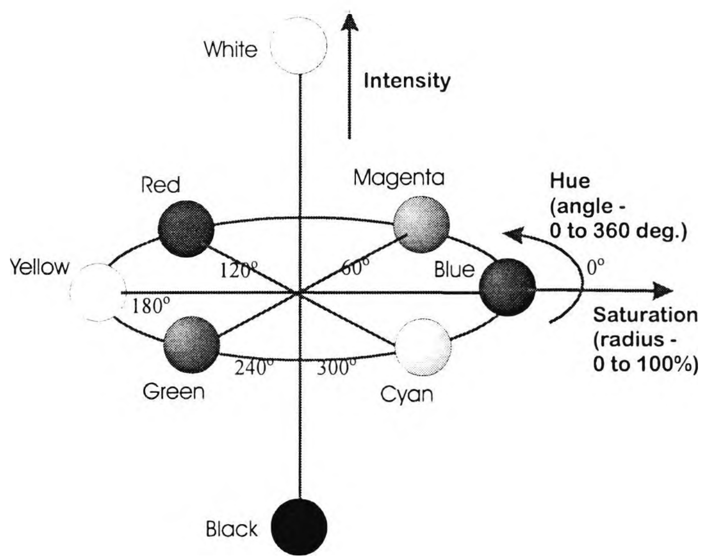


Figure 5.3 HSI colour model

5.5 Limitations of Colour Computer Displays

The limitations of displays to produce colour is better shown graphically by using the CIE (Commission Internationale de l'Eclairage) colour space (Figure

5.4). The purpose of this standard is to allow all colours to be defined as the weighted sum of the three primaries Red, Green and Blue (RGB system).

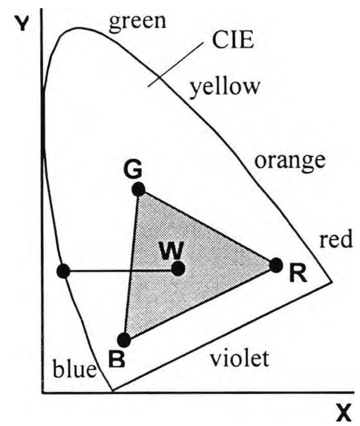


Figure 5.4 A CIE chromacity diagram showing a three-colour (RGB) system

Points within the enclosed area of the graph, known as the 'CIE space', represent colours which can be detected by the normal human colour vision system. The pure colours of the visible spectrum are arranged around the edge of the CIE space. The point marked 'W' in the colour space indicates white. The points on a line starting from the edge of the colour space to the point 'W' represents the desaturation of a pure colour.

The effects of mixing colours is represented effectively by the CIE space. Mixes of two colours lie on a straight line drawn between the two colour vertices. Similarly, mixing three colours will produce a colour which falls within the triangular area formed by the three different colour vertices. Colours outside such a triangle cannot be produced by any combination of the three colours represented by the triangle's vertices.

Colours in computer displays are formed by light emitted by three colour phosphors, of which a third is red, a third green and a third blue. The position of these colours are shown on the CIE chromaticity chart as R, G and B. As can be seen in Figure 5.4, the range of displayable colours on a colour monitor is considerably smaller than what the human visual system is able to detect.

Hence, the limitations of a CRT to produce colour is dependent on the red, green and blue phosphors of the display. Other limitations include the inability to reproduce darker shades, limited brightness, and lower resolution in comparison to its monochromatic equivalent.

5.6 Limitations of the Human Visual System

In the previous section, we looked at the limitations of computer displays to reproduce true colours. Another very important consideration which the display designer should consider is the limitation of the human visual system in processing colour. An overview of the human visual system now follows, to aid in the understanding of the causes of some of the limitations of the human visual system.

5.6.1 Physiology of the Visual System

Light enters the eye through the pupil causing an image to be formed at back of the eye (retina). Two lenses focus the light on the retina: a fixed lens (cornea) at the front of the eye and a variable-focus lens (lens) inside the eye, see Figure 5.5.

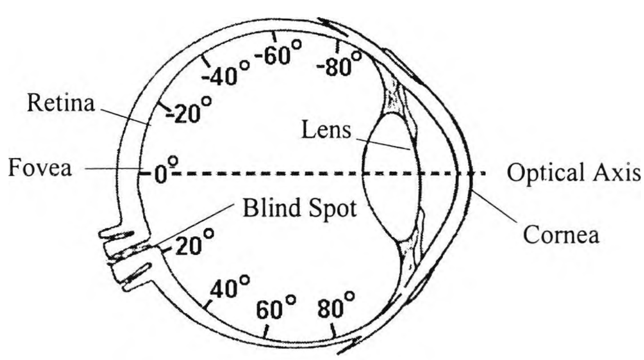


Figure 5.5 Cross-section of a human eye

A lens passes light of all wavelengths if the light is aligned with its optical axis. If light is not in alignment with the optical axis, the shorter wavelength light will form an image further away from the optical axis than longer wavelengths. Individuals can have the optical axes either aimed inwards or outwards.

In the former case, blue (short wavelength) images will appear to float on a red (long wavelength) background. The latter would cause the opposite effect. This effect is known as chromostereopsis. There are no means of correcting this problem as individuals would pertain to one or the other. The only solution to this problem is to avoid using colours from opposite ends of the visual spectrum.

The lens absorbs almost twice as much energy in the blue region as in the yellow and red. Furthermore, pigments in the centre of the retina (fovea), about 0.3mm in diameter have the same effect of absorbing blue wavelengths. This makes the eyes even less sensitive to the shorter wavelengths like blue and further enhances the sensitivity to longer wavelengths like yellows. The lens gets yellower as it ages which causes further insensitivity to blues. In addition, ageing reduces fluids in the eye, which causes colour to appear less vivid and bright.

5.6.1.1 Photoreceptors

The retina contains a large number of irregularly arrayed photoreceptors called rods and cones, named in accordance with their physical appearance. These different receptors are each best at absorbing light of different wavelengths. Rod receptors are very sensitive to light, but saturate at high levels of illumination, being used for vision at low light levels. These receptors cannot be used to detect colour as they have the same characteristic pattern of sensitivity to light of different wavelengths.

The human colour-recognition system is constituted of three populations of photoreceptor cones, each of which absorb different wavelengths of light most strongly. The three main receptors have peak sensitivity to light at different wavelengths -long (575nm), medium (535nm) & short (445nm) which corresponds to the colours red, green and blue respectively, see Figure 5.6. Hence, these receptors are commonly known as the red, green and blue receptors.

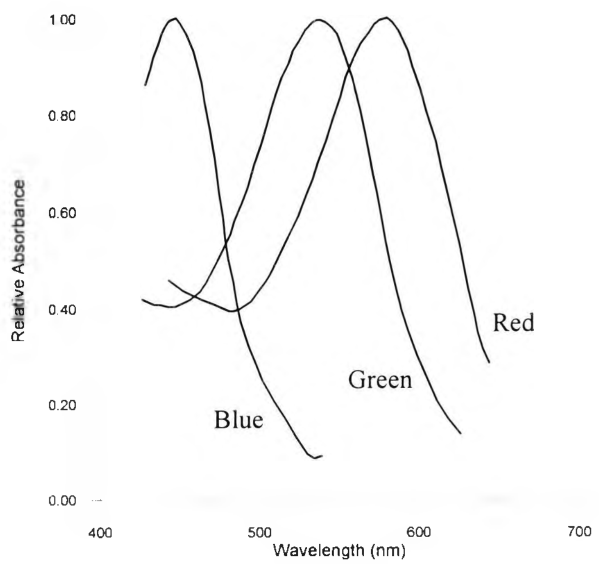


Figure 5.6 The relative absorbency curves of each Red, Green and Blue cone cells

Red receptors are found in 64% of the cones, green in 32% and blue in about 4%. The concentration of rods and cones around the retina are shown in Figure 5.7 (Cornsweet, 1970). The cone receptors are concentrated in the fovea, and dilute dramatically as one moves to the periphery of the eye. Moving away from the fovea, the density of rod receptors increases to predominance. The point from which the optic nerves leaves the retina is devoid of any receptors, this is called the blind spot. Though the eye sees nothing at the blind spot, a person is never conscious of emptiness or blackness. The brain fills in with whatever happens to be in its surroundings.

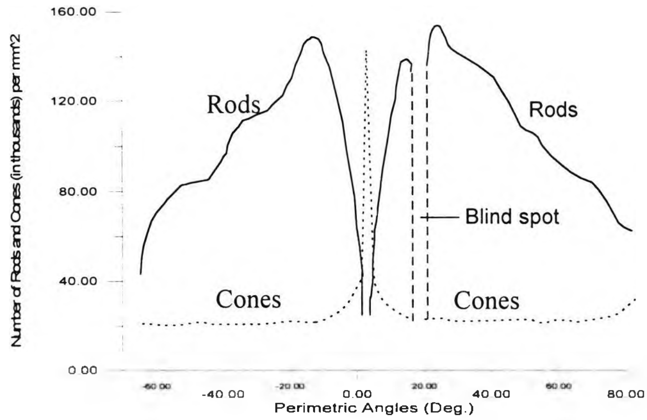


Figure 5.7 Distribution of rods and cones in the human eye

The three signals that register red(R), blue(B) and green(G) are not sent to the brain in a straight forward fashion where it is to be further analysed, but in the following vector form: (R-G), (R+G) and (R+G)-B. The first signal is effectively the ratio of Red/ Green, the second gives the brightness of the edges and the third gives the ratio of Yellow/ Blue. Two points are learnt from this, first, the eye is unable to discern yellowish blue or reddish green and secondly, the eye is a poor detector of edges if the edge differs only in blue.

The eye detects the shape of an object by determining its edges. Object edges can be determined by either the differences in colour between the object and its surroundings, differences in brightness, or both. However, colour difference alone, with no brightness difference, has been shown to be a poor discriminator of edges (Wolfe,1983). For example, to achieve optimum legibility, the luminance ratio between character and background should be selected to be between 5:1 and 10:1. Furthermore, dark characters on light background, in 'positive polarity', need bolder fonts than light characters on dark background because of the apparent spread of the light areas. Therefore, if the adjacent colours have no brightness difference; and an edge needs to be visible, then the region should be separated using a fine black line.

The red and green receptors are concentrated in the centre of the retina, while concentrations of blue receptors are found further in the periphery of the retina. Furthermore, the pigments in the fovea have the effect of absorbing the blue wavelength. These contributing factors have the effect of causing small blue objects to disappear when they are fixated upon. Blue-blindness comes into effect at sizes less than around 0.25 degrees of visual angle (around the width of a match head viewed at a distance of 700mm). Blue, especially saturated blue, should therefore be avoided where possible for the design of fine spatial details, such as small text or intricate graphics.

The human visual system is not only very poor at resolving small intervals in space, when vision is dependent on the short-wavelength cones, but also in time. This effect can be easily shown by carrying out an experiment with two bars, one red and the other blue, flickering at the same rate on a yellow background. The yellow background serves to reduce the sensitivity of the long and medium wavelength receptors, so that the blue bar is visible only by means of the short wavelength receptors. As the rate of flicker is increased, a range would be found where the blue bar seems to appear steady and unflickering while the flicker of the red bar still appears to be visible. Hence, blue lights require a slower blinking rate than red lights, if such blinking is to be seen.

Perceived flicker increases linearly with the logarithm of luminance, therefore a display which does not perceive to flicker at low luminance may well do so at higher lumination. Flicker sensitivity also increases as one moves into the periphery of the retina. Therefore, the eye is more sensitive to flicker at the periphery of a display system.

5.6.1.2 Colour Blindness

Colour blindness is an abnormality of the eye by which a person cannot distinguish colours. Approximately 9% of the adult male population and about 0.5% of females have congenital impairment, commonly manifested as the inability to distinguish red from green. Other forms include confusion of reddish blues with greenish blues, or yellowish reds with yellowish greens. Total colour blindness (monochromatism) is extremely rare. Overall, about 2% are afflicted to an appreciable extent.

There has been extensive research on the relationship of molecular genetics and colour blindness (Nathans, Thomas, & Hogness, 1986). Findings explain why men are more susceptible to inherited colour blindness then women. As has long been inferred from the patterns of inheritance of colour blindness: a man, since he inherits only one X-chromosome, will always exhibit colour blindness if his mother passes on to him an aberrant gene, whereas a woman, having two chromosomes, must normally inherit the aberrant gene from both parents before she will be overtly colour blind. Colour blindness may not only be inherited but it may be acquired. Cases of acquired colour blindness, however, usually involve a general deficiency of vision. There have been reports of colour blindness being acquired by people who drink alcohol or smoke tobacco heavily; reduced smoking has been known to restore normal colour vision.

5.6.1.3 Colour and Night Vision

Night vision has been well researched in the armed forces both in England and America (Birren, 1990). Their objectives are to develop methods and means to achieve the best possible visibility in darkness. The aviation industry, too, has gained much from research in this field in creating flight panels of aircraft which achieve good visibility of instruments under poor lighting conditions.

When the human eye is dark-adapted, sensitivity to long wavelength light (red) is relatively less than sensitivity to short wavelength light (blue). This can be explained by the uneven distribution of the red, green and blue receptors. As previously stated, red and green receptors are concentrated in the centre of the retina, whereas blue receptors are more often to be found in the boundaries of the retina. In other words, the colour red is seen distinctly only in the fovea of the eye and is hardly visible in the periphery. Red light therefore does not disrupt dark-adapted vision of the rod receptors. Instruments and dials, for example, are more sharply focused at night if illuminated by red light.

5.6.2 Luminance, Contrast and Brightness

It has been shown that practically all perceptual experiences are non-linearly related to the physical event. This includes the perceived brightness of display systems in relation with the intensity of current used in augmenting luminance on a display system. With perceive brightness, this varies almost logarithmically to the intensity of the beam current used in the display system. Nowadays, certain display systems take this perception problem into account by providing beam intensity that is inversely proportional to the perceived brightness.

Perceived brightness also depends on the brightness of the adjoining areas, as shown in Figure 5.2. An object is said to be chromatically induced when the surrounding colour of the object induces a perceived change of colour in the object itself. These perceived changes are in the direction of the complementary colour to the one that produces the effect (Walraven, 1976, 1977). For example, a red surround will produce a hue shift in the direction of green.

In viewing hue, there is a tendency for the eye to produce a strong opposite response. This is known as the successive contrast effect and can be explained by carrying out a very simple experiment: look at a saturated red square for at least 10 seconds and then shut your eyes. The after-image of the red square would be a green square. This experiment can be repeated with any colour. The effect has been explained in terms of the desensitisation of the colour looked at in the image. When the colour image was removed the complementary colour took its place in order to restore equilibrium to itself. However, recent scientific experiments indicate that after-image effects take place in the brain rather than in the eye itself. Hypnotised subjects have been asked to concentrate on a colour stimuli in their minds eye (imagination). Though the subjects saw nothing in the first instance, the subjects still 'saw' a complementary after-image, despite the fact the retinas of their eyes had not been activated (Walls, 1942).

Varying luminance of a light beam whose wavelength is held constant, will usually cause a perceived hue shift (colour change). This is known as the Bezold-Brucke effect. This again can be explained by the non-linear relationship of perceived brightness to luminance intensities. For example, increasing the luminance of the colour yellow would cause it to shift towards the colour white, while reducing its luminance will shift it to the colour brown.

Contrast is related to the both the luminance of the object and its background and is defined by the Commission Internationale l'Eclairage (C.I.E.) to be as follows (Thompson, 1984):

$$\text{Contrast} = \frac{L_o - L_b}{L_o}$$

where L_o = luminance of object
and L_b = luminance of background

Luminance and contrast are therefore physical quantities, whereas brightness is a psychological perception of intensity. Some hues appear brighter even though their luminance is the same. If a series of colours with equal luminance, ranging the visual spectrum, where shown to observers to pick out the brightest colour, the most picked colour would be about the 570nm range. This range corresponds to the colour yellow.

5.6.3 Cognition and Colour

Cognition concerns colour use where the observer may already have some expectations as to their meaning. These expectations could be due to their association with natural, geographical, emotional, cultural or technical contexts.

Therefore, it is appropriate, where feasible, to design a layout by first listing the expectations of users as to what they would like to see on the display, including colour. The technical context of colour, where used, is better defined globally than the expectations discussed earlier. Designers, therefore, have to be alert to common expectations about colour codes.

Even in some situations where there seems to be a good real world metaphor for the use of colour, the outcome can be unexpected, as in the experimental prototype performed by Salomon (1990) of Apple Computer Corp. The object of the project was to use colour coding metaphors of the real world to depict the age of documents on the Apple Mac system. Recent documents were depicted as icons filled with white and as documents got older they were depicted as a gradation of yellow. Deep yellow was used for the oldest document. The outcome was unexpected, because the colour selection seemed logical. However, the deep yellow of older documents leapt out of the screen, and the current document completely negated, being white. This was finally improved with the use of yellow for new items and several gradual duller shades of brown to depict the ages of older items.

5.7 Colour Preferences

At least 50 authoritative tests have been made on human colour preferences (Birren, 1992). The findings are so complete and uniform that not much doubt can be placed on them. Tests on babies have shown that they are most attracted to bright and rich hues. In older children, colour preferences were found to be in the following order: red, blue, green, violet, orange, yellow, and with maturity, the order of colour preference were as follows: blues, red, green, violet, orange, yellow (Eysenck, 1941). The latter finding involved 21,060 individuals.

People prefer colours they come to expect. Therefore, it is appropriate, where feasible, to design a layout by first listing the expectations of users as to what they would like to see on the display and this include colour. Usually the technical context of colour, is better defined globally, but that of natural, emotional and cultural expectations can be very different, therefore the designer has to be alert to common expectations about colour codes. For example, in contrast to the Western concepts, some Chinese might argue that red should stand for 'go', since the colour was seen as symbolising progress. To Westerners, blue would represent 'cold' but the Chinese equate white as being 'cold'.

5.8 Guidelines on the Effective Use of Colour

Based on the foregoing coverage, a compilation of guidelines on effective colour selection and usage follows. To make it practical, each guideline has been made as brief as possible and, where necessary, examples are given for clarity. The guidelines are divided into the following categories:

1. General Rules
2. To Identify
3. To Inform
4. To Please
5. To Depict
6. Allowing for the Limitations of the Human Visual System
7. Allowing for the Limitations of Individuals
8. Colour Coding Aids

Guidance for Colour Use

1. *General Rules*

1a. Develop in monochrome first:

The use of colour can best be realised by first developing the computer application in monochrome. This way, not only does one reinforce the informational content of the display when colour is added, but also cater for users of monochromatic displays and users with defective colour vision (Travis, 1991, Shneiderman, 1992; Galitz, 1993).

1b. Conservativeness:

Use colour conservatively as the benefits of colour decreases with over use. As the number of colours increases, the time to respond to a single colour increases and the probability of confusion increases (Luria et al., 1986). Limit the use of colour to about 7 ± 2 with greater emphasis on the lower numbers (Halsey and Chapanis,1951; Miller, 1956; Brooks, 1965; Frey et al., 1983). For novice users, four distinct colours are appropriate.

1c. Consistency:

Be consistent in use of colour (Kreb et al., 1978, Galitz, 1981). Colour should be consistent within a screen, throughout set of screens and throughout the system. This will give the users a sense of the relationship of colour in space, and time, thereby linking elements not immediately together.

2. *To Identify*

2a. Grouping:

Use colour coding to help group related items together or to differentiate unrelated items whether on a single screen or multiple screens. Use similar colours to relate separated fields of data.

2b. Distinguishing:

Use contrasting colours to distinguish data - select no more than four or five colours widely spaced on the colour spectrum, e.g. red, yellow, green , blue and brown (Smith, 1988, Marcus, 1986b) .

2c. Colour coding:

Define a colour code when colour is used only to distinguish unrelated items or where colour meanings have no existence. A very good example of this is the London Underground map, where colours are chosen to represent the various lines.

2d. Redundancy:

Design the layout with other information cues such as shape, pattern, position, size, texture, intensity, reverse video and flashing and thereafter add colour to reinforce and/or increase its informational density (Kreb et al., 1978, Robertson, 1980, Brown et al., 1980, 1983).

2e. Highlighting:

The use of colours to highlight an item on screen is analogous to the use of a highlighting pen on a piece of document. It is a good method of getting attention but only as good as its conservatism of use.

2f. Attention:

The eye is drawn to bright items. It is another good way of getting attention. The perceived brightness of colours, from most to least, is white, yellow, green, blue and red.

2g. Searching:

Colour can be used effectively in searching for items on a display (Christ, 1975; Kreb et al., 1978; Galitz, 1981).

3. *To Inform*

3a. Use colour changes to indicate different states:

Colour changes are good attention grabbers, but should be used in moderation. They can be used effectively in warning or danger situations, e.g., a change from green to red could signify danger levels of heat in a boiler system.

3b. Signifying action:

Use warm colours to signify action or the requirement of a response, and use cold colours to indicate inanimate things, passivity, status or background information.

3c. Grey-scale or Hue-based?

Use grey-scale intensities for quantitative changes and hue-based codes for qualitative changes.

3d. Expected colours:

Use colours which users may already have some expectations as to their meaning. Table 2 below, gives some colour stereotypes (Bergum & Bergum, 1981).

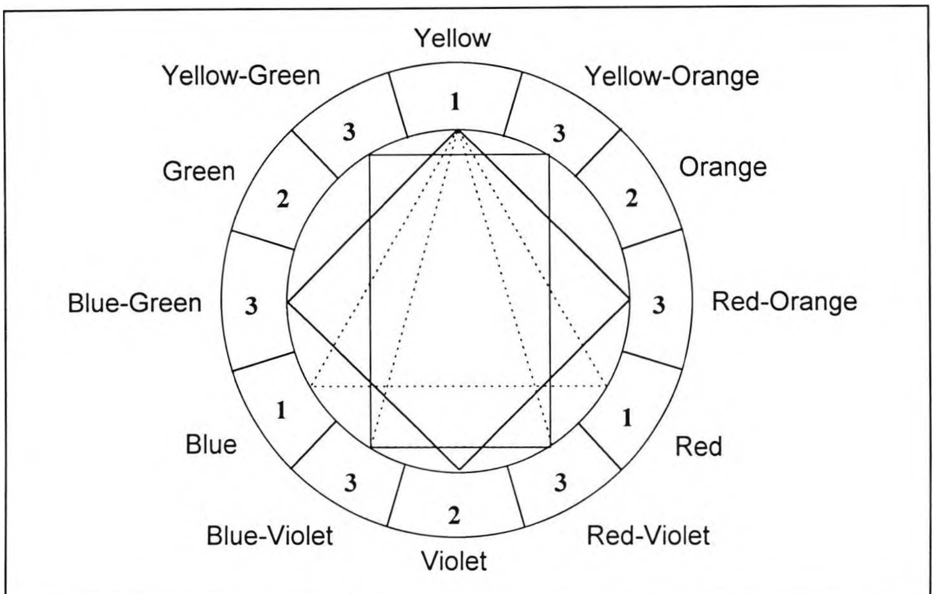
Table 5.2 Some typical colour associations

Colour	Meaning	% Association of Colour & Meaning
Red	Stop	100
	Hot	94
	Danger	90
Yellow	Caution	81
Green	Go	99
	Safe	61
Blue	Cold	96

4. *To Please*

4a. Use a Spectral Colour Wheel to create harmony:

The spectral colour wheel can be used as a guide to colours that harmonise or discord (Figure 5.8). Colours directly opposite to each other in the colour wheel are referred to as complementary colours. Such colour combinations are strong and can sometimes produce that resonate, especially when juxtaposed to each other. According to Itten (1964), all triads (shown dashed in the figure), and tetrads forming squares or rectangles, are 'claimed' to be harmonious. Taking the square as an example, yellow, violet, red-orange, and blue-green are harmonious colour combinations. These colour combinations are known as 'chords.' Other colour chords can be achieved by simply rotating one of the four depicted geometric shapes in Figure 5.8. The primary triadic colours (yellow, red, blue) are the best triadic grouping, but as the colour combination becomes more tertiary, the triadic colours can appear quite jarring (Champs, 1996). Analogous colours are three adjacent colours, such as yellow-green, yellow, and yellow-orange. Such compositions are harmonious because two of the colours contain the third.



1. Primary colours **2.** Secondary colours **3.** Tertiary colours

Figure 5.8 Spectral Colour Wheel

4b. Grey-scale colours:

Harmony is easily achieved with a grey-scale palette. Different lightnesses are established through mixing the selected colour with black or white.

4c. Colour preferences:

Children prefer bright and saturated colours as they are visually exciting. With maturity, comes liking of hues of shorter wavelengths, like blue or green. The order of colour preference for adults is as follows: blue, red, green, violet, orange, yellow (Birren, 1992).

5. *To Depict*

5a. True to life:

In using colour to depict objects in the real world, use colours that are true to life.

6. *Allowing for the Limitations of the Human Visual System*

6a. Avoid the simultaneous display of highly saturated colours:

Avoid the use of highly saturated colours from the opposite ends of the spectrum, such as red with blue (Ostberg, 1982; Sivak and Woo, 1983;

Murch,1984 and the Human Factors Society, 1988). Other colour combinations include red/green, blue/yellow and green/blue. These colour combinations create vibrations, illusions of shadow and after-images which can be very distressing to users.

6b. Use an appropriate luminance ratio between character and background:
The luminance ratio between character and background should be selected to be between 5:1 and 10:1 for optimum legibility. Dark characters on a light background, in "positive polarity", need bolder fonts than light characters on dark background because of the apparent spread of light areas.

6c Avoid the need for colour discrimination in small areas.

6d. Avoid adjacent colours differencing only in the amount of blue.

6e. Avoid the use of small blue objects:
Avoid saturated blue for the design of fine spatial details, such as small text or intricate detail. Use blue for large areas, such as slide or screen backgrounds.

6f. Make at least 10% changes in RGB values in order to make the difference discernible.

6g. Consider that the level and direction of ambient light affects the appearances of colour.

6h. Consider that the magnitude of detectable change in colour varies across the spectrum.

6i. Avoid using differences in colour alone to detect edges:
Use different brightness levels or a black thin line to separate the regions for a better edge detection.

6j. Avoid the use of red and green in the periphery of large display systems.

6k. Use blue, yellow, white and black in the periphery of large displays as the retina remains sensitive to these colours in the periphery.

6l. Use red for dark adapted vision:
Use red in the illumination of instruments and dials in dark environments as red illumination does not disrupt the dark-adapted vision of the rod receptors.

6m Do not assume linearity in grey-scale images as intensity is increased.

6n. Consider that different hues have inherently different saturation levels.

6o. Consider that not all colours are equally readable or legible.

6p. Consider that hues change with intensity and background colour.

7. *Allowing for the Limitations of Individual Users*

7a. Use brightness cues:
With age, people lose the ability to discern blue hues and hence require brightness cues to discriminate colour and fine spatial detail.

7b. Restrict the use of red and green for distinction:
As red/green colour blindness is very common. Others include a confusion of reddish blues with greenish blues, or yellowish reds with yellowish greens.

7c. Avoid single colour distinctions for colour-deficient observers.

8. *Colour Coding Aids:*

8a. Indicating actions. Use warm colours - Red, orange, yellow.

8b. Drawing attention - White, yellow, red.

8c. Background or predominant display. Use cool colours - Green, grey, saturated blue, any desaturated colour.

8d. De-emphasis, shading, non-critical data - Low saturation and low hue colours, saturated blue.

8e. Alarms, errors, stop, hot - Red.

8f. Secondary alarm colour - Pink.

8g. Warnings or data that require attention - Yellow.

8h. Normal or go - Green.

8i. Cold temperature or water - Desaturated blue.

8j. Colour combination in order of highest visibility - Yellow on black, green on white, red on white, white on blue, black on white.

8k. Ordering data. Use the spectrum - red, orange, yellow, green, blue, violet.

8l. Separating data. Use colours from different parts of the spectrum - Red/green, blue/yellow, any colour/ white.

8m. To group and show similarity. Use colours which are close neighbours in the spectrum (orange/yellow, blue/violet) and of similar brightness.

5.9 Implementing Colour Guidelines

There are various methods for colour design guidelines to be implemented in the GUI design process. The first method, as described above (Section 5.8), is in the written format. This however, is not the best method, especially when one is designing by computer. A better method would be to have these guidelines online. The easiest method of placing these guidelines online, would be to incorporate them into a hypertext help-file. Such help-files are typical of most Windowing applications. Ultimately, these guidelines could be incorporated into an expert system, or an expert system/ neural network hybrid.

Such applications already exist in the form of a database or a knowledge base. ColorUp Palette Chooser (Pantone, Inc, 1993) is an example of this. In this application, a number of foreground colours are recommended for a particular screen or slide when the user chooses a desired background colour (Figure 5.9). A preview of the colours schemes are shown in a colour palette and on a sample output screen, as in Figure 5.9. Such 'colour choosers' generally incorporate colour guidelines in a very subtle way, i.e., without directly stating any of them. What it does, is propose a few colour schemes, some of which are based on a colour designer's intuitive instinct rather than any particular rule. An expert system is not capable of capturing this form of intuitive knowledge and yet, a database like the one in the example provided, is often limited to colour selection of a fixed nature.

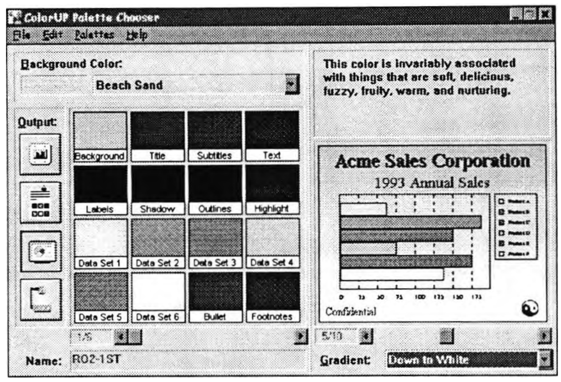


Figure 5.9 A typical colour scheme selector incorporating colour design guidelines

A neural network colour recommender, however, has the capabilities of capturing the intuitive knowledge of colour experts. The benefit of a neural network application is that it is not fixed by what is in a database, as it is capable of producing its own colour schemes based on 'learned' knowledge. Research on developing colour advisors for user interface design have already started for a number of years (Salomon & Chen, 1989; and Meier, Byte Magazine, May 1991). Both researches were for the Macintosh GUI, the former is based on using neural networks while the latter is based on a knowledge base system. Both projects have already shown great strides in providing effective colour advice.

5.10 Conclusion

There are four main ways colour can be used in HMI; to identify, to inform, to please, and to depict. There are also four human factors to take into account when designing with colour; physiology, perceptual psychology, expectation, and preferences. With regard to physiology, designers should consider the following:

1. Individuals have optical axes that either aim inwards or outwards when incoming light is not aligned with the optical axis of the eye. This causes the effect known as chromostereopsis, whereby colours from opposite ends of the spectrum appear in different viewing planes. Prolong viewing of such

colour combinations can lead to eye fatigue, as the eye has to continuously refocus when viewing the two colour combination.

2. The lens of the human eye absorbs almost twice as much energy in the blue region as in the yellow and red. Furthermore, there are 64% red colour receptors, 32% green and only 4% blue, in the eye. Red and green receptors are concentrated in the center of the retina, while concentration of blue receptors are found further in the periphery of the retina. The combination of these factors, make the eye less sensitive to the shorter wavelength like blue.
3. The three signals from these receptors, however, are not registered directly as they are, but in a vector form: (R-G), (R+G) and (R+B)-B. Such registrations make discerning yellowish blue, reddish green, and edges differing in blue only, difficult to the human eye.
4. Colour blindness affect 9% of the adult male population, and about 0.5% of females. The most common colour blindness is between red and green, others include reddish blues with greenish blues, and yellowish reds with yellowish greens.

As for perceptual psychology, the following considerations should be made:

1. The perceived brightness of display monitors does not correspond directly with intensity of current used, but almost logarithmically.
2. The perceived brightness of an object depends on its surrounding brightness.
3. Prolonged viewing of hue, creates a tendency for the eye to produce a strong opposite effect.
4. Changing luminance of light whose wavelength is held constant, will usually produce a perceived hue shift (Bezold-Brocke effect).

The expectation of colour is very dependent on natural, geographical, emotional, cultural, and technical context. Colours used in a design, should be based on these, where relevant. With colour preferences, however, children tend to favour colours in the following order: red, blue, green, violet, orange, and then yellow. In adults, this preference is very similar, except the former two colours (red and blue) are in opposite order.

The next chapter, covers the subject on icons, which forms a natural progression to the implementation of the guidelines included in this chapter.

6. Icons - Graphical Elements

6.1 Introduction

The work in this chapter, and the next, on screen design, follows on the developments of the previous. No matter how well an icon or a screen is designed, the mindless use of colour will often make the difference between a usable, and an unusable application. It is therefore, imperative that the colour guidelines of the previous chapter be followed in the design of both icons and screens.

This chapter examines icons, their importance, and how they can be designed to improve the effectiveness of a user interface. The chapter starts by providing an iconic definition and goes on to building an iconic taxonomy. Following this, a discussion is provided on the advantages of using icons at the interface. A design process for developing icons is presented, along with a method of selecting objects while taking graphical context into consideration. To assist developers of iconic interfaces, the author has compiled a guideline on iconic design representations with examples. Observations are then given on building iconic families, and methods of enhancing icon understanding. Finally, coverage is given on an iconic evaluation methodology, and the elements that need consideration during this process.

6.2 Icons

Icons are pictorial symbols on a computer display that suggest the purpose of an available function. The computer industry defines icons as any small pictorial symbols displayed by an application. The introduction of the Xerox Star system, in April 1981 (Byte, 1982), brought with it many new innovations. One of which was the first commercial employment of icons at the computer interface. The impact was the divergence from the commonly known text-based command-line and menu-based interfaces to one that is truly graphical. This new interface style is known as the graphical user interface (GUI). Popularized by machines like the Macintosh, the GUI has had a huge impact on the usability, usage, and usefulness of computers. The GUI is found on almost every current computer platform, ranging from personal computer systems running Macintosh, Windows or Presentation Manager to workstation class machines with NextStep, X Windows, OPEN LOOK or Motif windowing systems. Since the emergence of the GUI, there is little question that computers are seen to be more accessible. Figure 6.1 depicts a screen shot from Microsoft's Windows 95. Such a windowing environment is typical of most GUIs. Every element in it, besides text and window border, is an icon. Icons are, therefore, the building blocks of GUIs.

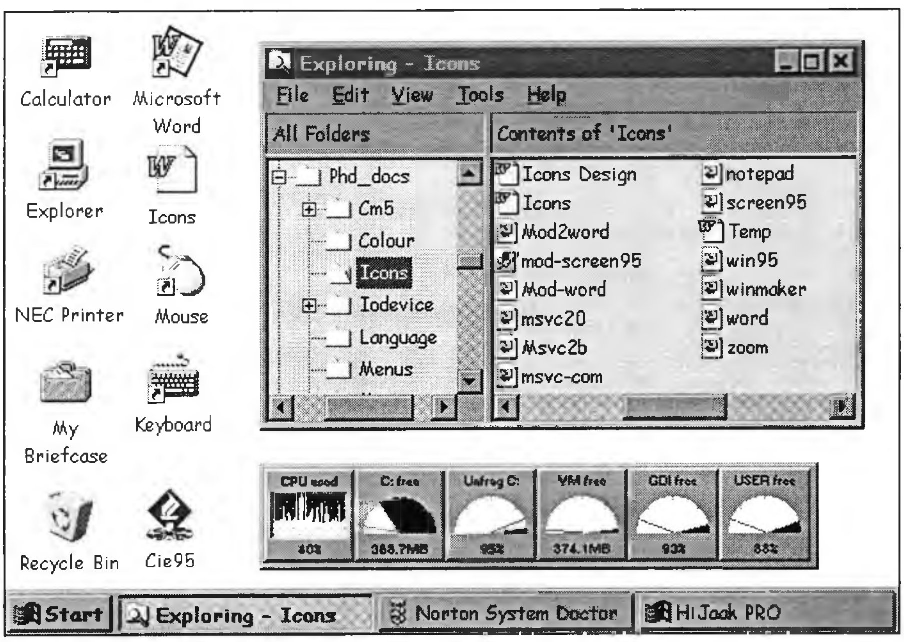


Figure 6.1 Screen snap shot of a typical Microsoft Windows 95 working environment

6.2.1 Icon Taxonomy

Charles Pierce (1955), one of the founders of the field of semiotics, categorized icons into three groups; icon, index or symbol. According to Pierce, the icon shares similar characteristics to the object it is trying to represent. Looking at Figure 6.1, all five icons down the far left column are thus icons, as they all share similar characteristics to the objects they represent. An index, however, refers to that which caused the sign to exist and depends on the associated object in some non-arbitrary way. For example, the presence of foot prints in the hallway logically infers that someone has been through that point. Without the prints, no such conclusions can be made. Hence the foot prints in this case provide an index to the event occurring. Index therefore tends to represent a concept rather than a particular object, whereas icons tend to represent physical objects. The real-time histogram chart and analogue gauges used to monitor the system resources shown in Figure 6.1, are examples of indexes. A symbol, however, is an arbitrary graphical representation of the object it is trying to represent. Examples of symbols abound in road signs. Road signs are given arbitrary graphic shapes for example, to represent different meaning. Circular shape signs give orders, triangular shape signs provide warning and rectangular signs mainly furnish information. In Figure 6.1, the three signs (dash, rectangle and a cross) in the three top right "buttons" of the "Exploring" window are examples of sign icons.

Other researchers have provided similar or extended versions of Pierce's iconic taxonomy. Arnheim (1969) and Lodding (1983) has an almost identical categorization, of picture/ pictograph, symbol and sign. Marcus (1984) classifies icons into representational, semi-abstract and abstract classification, while Gaver (1986) categorizes them as metaphorical, nomic and symbolic. All four iconic categories, corresponds closely to Pierce's iconic classification, see Table 6.1. Similar iconic taxonomy have also been proposed more recently by Webb et al. (1989), Blattener et al. (1989), Rogers (1989) and Elliot et al. (1993). Table 6.1, provides a summary of how the history of iconic taxonomy fits within Pierce's traditional view of icon classification. Whilst, different researchers have provided distinct names for their iconic categories, the author finds that they essentially fit in with Pierce's (1955) view on iconic taxonomy.

Table 6.1 Chronological taxonomy of icons

		Icon Taxonomy		
Researchers	Year	Representational Icon	Symbolic Icon	Sign Icon
Pierce	1955	Icon	Index	Symbol
Arnheim	1969	Picture	Symbol	Sign
Lodding	1983	Pictograph	Symbol	Sign
Marcus	1984	Representational	Semi-abstract	Abstract
Gaver	1986	Metaphorical	Nomic	Symbolic
Webb et al.	1989	Pictorial icon	Symbolic icon	Sign icon
Blattner et al.	1989	Representational	Semi-abstract	Abstract
Rogers	1989	Resemblance	Symbolic	Arbitary
Elliot et al.	1993	Direct / Indirect iconic representation		Direct/ Indirect symbolic representation

Elliot et al. (1993) distinguishes between direct and indirect icons by the number of referents involved in an icon. A direct iconic or symbolic representation means there is only one referent involved, the denotative referent. Taking an example from Elliot et al., a picture of a computer mouse provides a direct iconic representation between the computer mouse and what it depicts, hence making it a denotative referent. An indirect iconic representation, however, involves at least two referents, a sign referent and a denotative referent, and the two being different. The 'rubbish bin' in Figure 6.1, is an example of an indirect icon. The sign referent of the 'rubbish bin' is a bin where disposable are placed. However, the denotative referent of the 'rubbish bin' in the computer application is a file removal program. Hence, in an indirect iconic representation, and unlike the direct, the sign referent and denotative referent are not one of the same.

6.3 Advantages of Employing Icons

Many users have come to see computers as being more user friendly with the advent of GUI windowing interfaces. This does not imply that such applications are easy to use, as this is depends on their design, but that it provides an environment conducive to designing 'easier to use' applications. Users tend to find learning such application easier than with the traditional command language interface style counterpart, because all commands are visible at the user interface. GUI interfaces are, therefore, based on recognition, rather than on recall of commands, and they also enable far more consistency across products, making for an additional reduction in learning time. A study comparing some file manipulation tasks using the Macintosh direct-manipulation interface system and Microsoft's Disk Operating System (DOS) command language system concluded that the former was better in respect to learnability, performance and subjective ratings (Shneiderman et al, 1987).

GUIs employ a 'direct-manipulation' style of interaction (Section 4.2.5), which is based on how we interact with real world objects. The term was first coined by Shneiderman (1982) to describe the ability to treat a visible entity, such as an icon, or filename, as an object. For example, most GUIs today are base on the office desktop metaphor, where such objects as a filing cabinet, folders, documents, notepads, calculator, rubbish bin is to be found (Figure 6.2). In such object-oriented user interfaces, icons are better representation of objects than word labels in terms of the provision for direct manipulation (Johnson, 1987). Objects are often manipulated by first selecting the required object or icon using a mouse and then deciding upon the action to be placed on it, such as delete, copy, and move. This interaction style corresponds closely to how we manipulate objects in the real world, hence making for a more intuitive interface. Additionally, direct manipulation actions in iconic interfaces do away with having to type commands, a source of errors.

Figure 6.2 Windows 95 icons representing elements in an office desktop metaphor. Starting with a filing cabinet and then moving on to a folder, a document, a notepad, a calculator and finally a rubbish bin

It has been shown that the capacity of memory for graphics may be unlimited. In an experiment by R.N. Haber (1970), subjects were shown 2,560 photographic slides (640 slides per day) at a rate of one every 10 seconds. After these slides, they were shown a pair of slides to determine which had been seen. Correct recognition rate were found to be as high as 85% to 95%. In order to determine if fatigue played a part in recognition accuracy, two subjects were shown all 2,560 slides in just two days. The two subjects displayed correct recognition at 89% - 90%, demonstrating that fatigue had no significant effect on pictorial recognition. The experiment also showed that subjects remembered concrete objects in action, better than their counterparts, as a near flawless recognition rate of 99.6% was achieved. Earlier work by Shepard (1967), produced similar findings when comparing the accuracy of recognition of words, short sentences and pictures. Words produced 88.4% correct recognition, short sentences 89% accuracy, and contrasted 96.7% correct recognition for pictures.

Icons have also been shown to enable a faster recognition rate than their textual counterparts (Hemenway, 1982). A study of road signs demonstrated that iconic signs can be read typically twice the distance and in half the time as word signs (Ellis et al, 1979). The reason behind this could be attributed to the graphical elements of an icon, such as its distinctive shape and colour. Pomerantz (1983) hypothesis that icons differing from each other in terms of their "global" features (e.g. shape, size and colour) would be searched and identified more rapidly, than icons differing from each other in terms of "local" features (e.g. lines and internal structures). Unlike icons, words, especially if all characters are in capitals, do not provide strong distinguishing features that promote quicker response rates. Furthermore, with textual information, users tend to read sequentially, until they stumble across the search word or phrase. This could take considerably longer than searching for an icon, as graphics can be assimilated at a glance, or in parallel.

The use of graphics in visual and spatial context is generally more natural than text. For example, it is often easier to understand and to follow a graphical DIY assembly instruction than it is to follow a descriptive textual instruction. Lodding (1983) suggests that the "inherent naturalness of image-assisted communication has motivated the development of the iconic interface." Icons can also benefit those with reading disabilities, such as dyslexia. In addition, icons can make an application more global in its usage (Kolers, 1969; Blattner et al, 1989). Icons provide a more global understanding because they do not rely on language, but universal signs or representations of objects or actions. Icons can also help to save screen space

(Hemenway, 1982), as they can convey more than an equally prominent word label or heading.

Many reasons have been given on the advantages of using icons in HMIs. Moreover, the fact that most applications written and used today are based on an iconic interface is a testimony to the preference.

6.4 Semiotics - The study of Icons

Semiotics is the general philosophical theory of signs and symbols that deals with their function in both artificially constructed and natural languages. It covers syntactics, pragmatics and semantics. Syntactics refers to the physical qualities (size, colour, texture etc.) and appearance (shape and orientation) of an icon that affect the ease with which visual signs can be distinguished and identified. Pragmatics refers to how the icon is produced and depicted. Pragmatism includes producing icons of sufficient size for visibility at normal viewing distances and making sure that the screen resolution is adequately high for image clarity. Semantics however, refers to the meaning of an icon which is dependent on both the context and viewer's mind. Context narrows the scope of possible meanings, but the final meaning taken by the viewer is dependent on the experience of the viewer with such representations. Hence, the graphical representation of an icon and context are the two elements a designer has control over for the meaning a user will place on an icon.

6.5 Icon Design Process

The purpose of the graphical representation of an icon is to convey the meaning, and hence, the functionality of an icon, while context helps to throw a light on the intended meaning. In order to provide the intended context, icons have to be designed from a holistic sense. To attain this overall perspective for an application, the design process should start with defining the main purpose (goal) of the application and then go on to describe the individual stages (sub-goals) needed to achieve that main goal. All tasks and processes are analyzed and defined to meet the intended users. Tools needed in performing each task are listed. All these are then integrated and organized to form a picture of the intended application. All the amassed information should now provide a good overall picture (mental model) as to how the application will work. To aid application understanding, navigation and remembrance; designers often employ metaphors (Section 6.8.2.2). The use of metaphors is based on suitability to application content and intended users. The use of metaphors will also dictate the graphical content of icons. With all the gathered information, the graphical representations of each individual icon can be decided, based on it's intended function, metaphor and context. The icons are then designed and tested to ascertain the icons presented, convey the intended functions. The execution of these stages is iterative in nature, each affecting the other.

Kaneko et al. (1991) has proposed a object-selection method of quantifying the relationship between object and the intended function. The method uses two measures; the frequency with which objects are answered by test subjects and the order in which they are answered using a weighted scheme. For each test subject, the first answer would be assigned a weight of 3, the second, 2 and the third, 1. These weights are then multiplied with each object answered and summed with all corresponding answers to produce a relationship score. Object or objects chosen to represent the intended function are selected by choosing the objects that scored highest and by a considerable margin. If margins are not sufficiently wide enough, all proposed objects with high scores may be considered equally good at facilitating recognition of the intended function. The result of their experiment (Kaneko et al. , 1991), showed that, for many functions, objects can be selected with high confidence of them meeting their intended function.

The object-selection method proposed by Kaneko et al. does not take into consideration contextual information. As previously discussed, context plays an important part in the understanding of icons. Hence, to improve the method, context can be taken into account by providing test subjects with a brief overview of the nature of the application, its goals and methods at the onset of the experiment. Additionally, a description of each task can be given, providing context with which users can base their object proposals as tools required in carrying out those tasks. By doing so, objects selected will be based on given indirect contextual information.

6.6 Iconic Design Representations

A study by Waterworth et al. (1993) found icons that represent concrete objects existing in daily life, geometrical or spatial concepts, or ones that had well-accepted standard symbols were recognized and understood successfully. Alternatively, icons that are abstract and lacking in physical representations, or icons that shared physical form with other icons produced far lower recognizability. Other studies by Green et al. (1983), and Rogers (1986), produced similar findings. Good icons were found to be mainly mnemonic, whereas bad icons were mostly arbitrary, while metaphorical icons had equal share of both good and bad. Therefore, when designing graphical representations for icons, it is best to start by looking for graphical elements that provide a natural and direct representation, selecting objects or actions that are most familiar to users. Preference should be given to graphical representations in the following order; representational, symbolic, and then sign icons. As one moves through the selection, one is moving from concrete to abstract representations.

Direct representational icons are the easiest to portray, as they depicts the subject directly. Indirect representational icons, however, depict objects, or actions by association to analogies, or metaphors. The drawback with indirect representations are that they are not always obvious initially, but once understood, they are easily recognized, and hardly forgotten. Analogies can come from showing analogous functionality, end results, structural connections and body parts in action. Examples of each are shown in Figure 6.5.

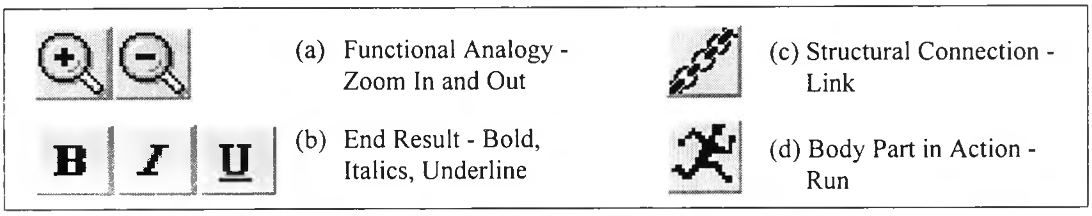


Figure 6.5 The different types of analogical representations

In functional analogy, an object commonly applied for such purposes, could be depicted to provide such functionality. For example, Figure 6.5(a) depicts two magnifying glasses with a plus sign and minus sign to represent zoom in and zoom out respectively. Another method of depicting analogy is by showing the end result or effects of a command. Figure 6.5(b) depicts three icon buttons commonly found on word processing toolbars. These buttons are used in text formatting; bold, italics, and underline. Computer programming building commands as 'link a program' could employ a structural connection in its graphical representation as in Figure 6.5(c). While 'run a program' after being built could employ a running human figure (Figure 6.6(d)) for such representations.

Metaphors are also commonly used in the representation of functionality, which is in itself based on analogy. It represents object, or action in a very imaginative manner. Metaphors come under various forms; synecdoche, litotes, hyperbole and euphemism (Horton, 1993). Synecdoche uses a part in the representation of the whole (Kolers, 1969). Figure 6.6(a) depicts an example of using a chess piece and a deck of cards in the general representation of games. In litotes representations, the affirmative is expressed by the negative of the contrary. For example, the X sign or the standard circle with a diagonal slash is often superimposed on the object or action to negate, as in Figure 6.6(b). Hyperbole means exaggerating and is commonly used in graphical representations to highlight the intended meaning of an icon (Hemenway, 1982). For example, in stating the severity of a problem, the bomb icon in Figure 6.6(c) is commonly displayed by Macintosh based applications when a system error occurs. Clearly, this is an exaggeration but its depiction does state the severity of the problem. Euphemism (Figure 6.6(d)) is the substitution of an agreeable or inoffensive depiction for one that may offend or suggest something unpleasant. Taking the example provided by Horton (1993), a plaster could be used to represent injury rather than a emotionally disturbing graphical representations. Blood for instance, makes certain people very emotionally distressed.

(a) Synecdoche - Games

(b) Litotes - Non-smoking

(c) Hyperbole - Fatal Error

(d) Euphemism - Injury

Figure 6.6 The different type of metaphoric representations

The design of an symbolic icon is more difficult to create as the designer has to focus on a particular aspect of concept, rather than on the object itself. Often, with symbolic icons, the icon is reduced to its essential elements in an attempt to focus upon that property of the image that carries the intended concept. A good example of a symbolic icon, is the silhouette of a broken wine glass, we tend to associate with the concept 'fragile.'

Sign icons are usually not well recommended in usage as they are arbitrary, and therefore, not well understood. However, there are many signs that have been well used, and learned in industry, and public places that could form an exception to this rule. In the engineering industry for example, there are countless number of graphical conventions used in design that could be applied to icons when designing applications for such users. Likewise, other graphical conventions used in other fields could be applied to the development of their respective iconic applications. Public signs are however, better understood by a wider range of people as they are encountered more often. Therefore, their suitability for iconic representations is better in comparison to using specific conventions when designing for the general public.

The message an icon is trying to convey can consist of textual information. Such texts however, have to be brief as icons are often small in size. Figure 6.7 shows how text can be used in different ways in iconic communications by giving examples of icons from four Windows applications. Figure 6.7(a) is the icon used by Netscape's Internet browser application and is an example of using initials as the main message in an icon. Figure 6.7(b) is the icon used by Microsoft Word for Windows documents and is another example of using initials but this time as an identifier to the application. Figure 6.7(c) uses the question punctuation mark as an identifying trait of Help files in Windows 95. Figure 6.7(d) uses word labels in identifying the Winmaker Pro application by depicting the name of its developer, Blue Sky.

(a) Netscape (b) WinWord (c) Help file (d) Winmaker Pro

Figure 6.7 The different ways of using text in icons

Once the object (representational, symbolic or sign) and context has been decided for an icon, the designer has to determine how to represent it graphically (syntactics and pragmatics). Here, the "PRACtical" screen design principles of Chapter 7 can be applied equally well to icon design. Icon design however, has to be looked at from a slightly different perspective, scale. Icons are much smaller to screens, and such concepts as clarity and simplicity (Byrne, 1993) play a greater part in iconic communication. As an aid to creating simple and clearer icons, Table 6.2 lists the maximum number of codes for effective human differentiation (Galitz, 1993).

Table 6.2 Maximum number of codes for effective human differentiation. (Compiled by Galitz, 1993. Data derived from Martin, 1973; Barmack and Sinaiko, 1966; Mallory et al., 1980; Damodarn et al., 1980; and Maguire, 1985)

Encoding Method	Recommended Maximum	Comments
Alphanumerics	Unlimited	Highly versatile. Meaning usually self-evident. Location time may be longer than for graphic coding.
Geometric Shapes	10-20	High mnemonic value. Very effective if shape relates to object or operation being represented.
Size	3-5	Fair. Considerable space required. Location time longer than for colours and shapes.
Line Length	3-4	Will clutter the display if many are used.
Line Width	2-3	Good.
Line Style	5-9	Good.
Line Angle	8-11	Good in special cases (such as wind direction).
Solid and Broken Lines	3-4	Good.
Number of Dots or Marks	5	Minimize number for quick assimilation.
Brightness	2-3	Creates problem on screen with poor contrast.
Flashing/ Blinking	2-3	Confusing for general encoding but the best way to attract attention. Interacts poorly with other codes. Annoying if overused. Limit to small fields.
Underlining	No data	Useful but can reduce text legibility.
Reverse Video	No data	Effective for making data stand out. Flicker easily perceived in large areas, however.
Orientation (location on display surface)	4-8	___
Colour	6-8	Attractive and efficient. Short location time. Excessive use confusing. Poor for colour blind.
Combinations of codes	Unlimited	Can reinforce coding but complex combinations can be confusing.

In a study by Green et al. (1990), learned abstract icons (sign icons) were found to be recognized faster than their representational icons varying in internal structural description (content). The representational icons used in their study represented text editing features from Arend's et al. (1987) earlier study, four of which are shown in Table 6.3. The figure also shows the corresponding abstract icons used in the study. The findings by Green et al. confirms Pomerantz's (1983) hypothesis. Icons differing from each other in 'global' features would be search and identified more quickly than icons differing from each other in terms of "local" features. In this instance, the complex internal structural description of the representational icons slowed the search process. This can be attributable to the additional mental processing required in controlling search and evaluating the appropriateness of searched icons to desired function. Another possible reason why the search times for the abstract icons were marginally better than the representational icons were because of their simplicity and their more distinctive shape.

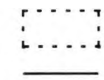
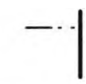
	Skip word ahead	Replace word	Move sentence	Justify text
Green's et al. Abstract icons				
Arend's et al. Representational icons				

Table 6.3 Corresponding abstract and representational icons used in Green et al. study

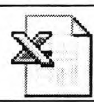
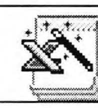
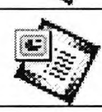
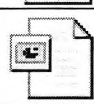
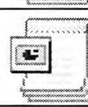
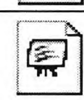
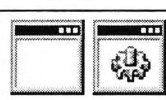
Another factor that was found by Green et al. (1983) to improve search time dramatically was the fixed locations of icons. This is often simple to achieve within an application (i.e., within toolbars) but impracticable at the common "desktop" (GUI operating system) level, where icons do not have any relationships to one another. At the desktop level however, placements of icons from one session to another should be consistent while being user customizable so as to attain some consistency.

6.7 Iconic Families

The basis for building iconic families is consistency. Table 6.4 shows a few icons from the Microsoft Office (MS Word, MS Excel & MS PowerPoint) applications, other Window applications, and MS DOS applications and batch files (both being executable programs). Note the consistencies within and between the applications listed in Table 6.4. The first row of Table 6.4 represent Microsoft Word for Windows (WinWord) file types. Notice the "*W*" symbol in all the icons, it is the trademark of the WinWord application. From this trademark, users know that all the icons associated with it belongs to or was created by the WinWord application.

Also note the consistencies between all the Microsoft Office application iconic representations. All data files consist of a graphical page or document, all templates of a thick pad, and all "Wizard" applications with the same thick pad and added wand. Other Window applications are also consistent. This is demonstrated by the data files created with the other Window applications which consist of the same graphical page or document along with the associated trademark of the program used in creating it. With Window application icons, all programs have their own distinctive iconic design and trademark so as being able to distinguish between them. DOS based applications, however, unlike Window based applications do not often have their own icon, hence a blank Window icon is used in its place. Batch files have a distinctive addition of a gear representing a customizable (re-engineerable) executable program. To further improve consistency, the help files of each application in Table 6.4, could include a trademark as in Figure 6.8.

Table 6.4 Some families of icons in Windows 95

Program	Application	Data File	Template	Wizard	Help
MS Word					
MS Excel					
MS PowerPoint					
FotoTouch & Hijack (Other Window Programs)	 	 			
MS DOS Programs & Batch File					

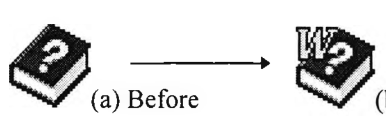


Figure 6.8 Improving consistency by including the appropriate trademark to the Help files

With some Window applications, different data file types can exist or be created. Table 6.5 shows how some Window based applications, differentiate themselves by including a basic graphical representational data content within their iconic document. Most Window applications, however, are capable of only generating a single data file types and are therefore represented simply as in Table 6.7, under the data file category. Table 6.7 also shows how similar icons (folders and data files) can depict their contents using representational and trademark icons within them.

Table 6.5 Different data file types depicted using a consistent appearance to it's program application

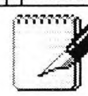
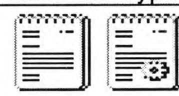
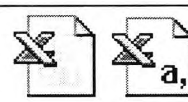
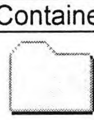
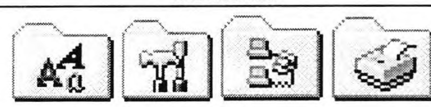
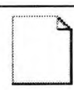
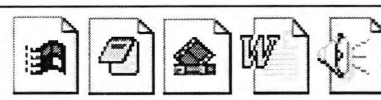
Program	Application	Data File Types
MS Write		
MS Excel		

Table 6.6 Using iconic contents to describe the contents of folders and data files

Description	Container	Contents
Folder		
Data File		

In short, iconic representations could consist of the following elements (modified version, Horton (1994)):-

Iconic File = File type (Container) + Data Type (Contents) + Application Trademark + Modifier (Characteristics)

where for example,

container = , content = , application trademark =  and

modifier = 

6.8 Improving Icon Understanding

6.8.1 Help Status Bar and Pop-up Help Notes

Two methods are currently extensively use to enhance the understanding of unlabelled icons in toolbars. The first method employs a status bar that provides a brief descriptive sentence of the functionality of the icon or menu option being pointed at with the mouse cursor. The status bar is commonly located at the bottom of the application's main window. The second method has had extensive use in the last few years and employs a pop-up help note describing the functionality of an icon. The help note pops up directly below the mouse cursor as in Figure 6.9 when the cursor is placed over the chosen icon for more than a second.

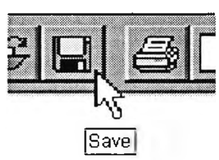


Figure 6.9 Pop-up help notes currently found in most Microsoft Windows based applications

With the introduction of Windows 95, there are two other additional methods of obtaining information about an icon or general help about parts of a window (Figure 6.10). The first method is achieved by first clicking on the question mark icon at the top right corner of a window (where available). This action causes the mouse cursor to change from a straight forward pointer to a pointer cursor with a question mark (Figure 6.10). Users then select the object to be questioned using the new mouse cursor, which then brings up the required help information in a pop-up window. A change in cursor icon, depending on functionality, is an effective method of informing users of status, as in this example; or prospective functionality. The latter can be seen when a cursor is positioned over a hot-spot, like the corner of a window. This causes the cursor icon to change from the typical arrow head icon, to an icon with two arrow heads, depicting the direction in which the window can be scaled.

The second method is more direct and is achieved by clicking the right mouse button on the object to be questioned. Where help information is available, a pop-up

"What's This?" menu is displayed, giving users the option to find out the purpose of the selected object. Again, a pop-up window as described in the first method is displayed.

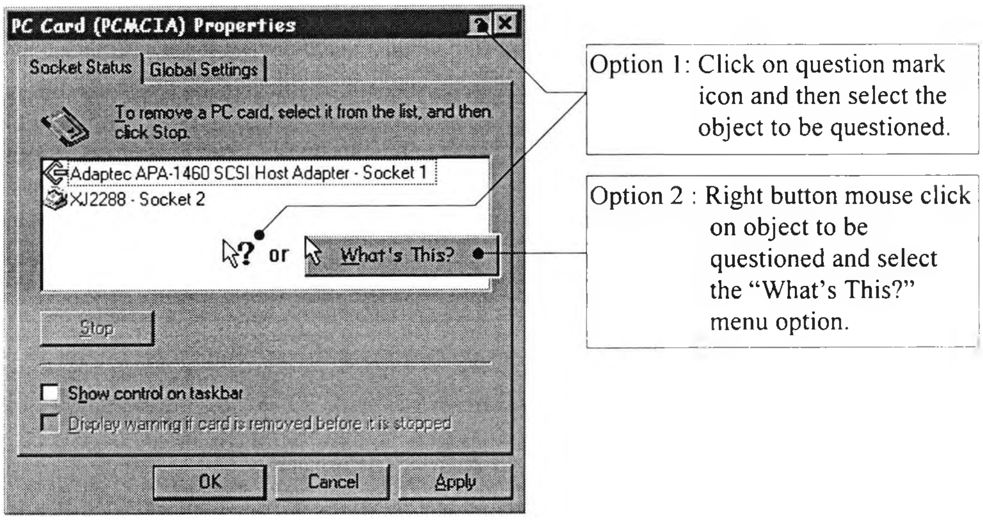


Figure 6.10 The latest pop-up help note from Microsoft Windows 95, available through two options

In applications that are not too cluttered with commands, an alternative can be considered to the pop-up help notes as in Netscape's Web browser. Netscape's alternative is the incorporation of the help note in the icon buttons themselves, as shown in Figure 6.11. Such alternatives are nothing new, as icons representing applications always had a similar brief note below the icon. Such notes do clarify and improve understanding.

Figure 6.11 The first three iconic buttons in the navigation toolbar of Netscape's Web browser

6.8.2 Animated icons

Another method of improving understanding, that has yet to be used extensively, is in the animation. Animation can be used to provide continuous real time data feedback, as in Pierce's index example of Figure 6.12 or in an action feedback when a user performs an action. An example of the latter can be seen in the Macintosh trash can icon. When a user drops a file into it, the trash can expands as in Figure 6.12 to indicate that something has been dropped into it.

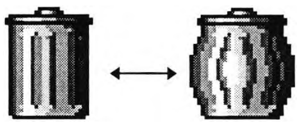


Figure 6.12 The Macintosh animated trash can

Animation can also be used to provide assistance in understanding the function of an icon by clarifying its meaning, demonstrating its capabilities and even explaining the method of use. Figure 6.13 shows an animated sequence of a printer icon and how in observing the animation, user will have a better understanding of the functionality of the icon. To have all the animation sequence running at the same time will not only be very disconcerting to the user but also take up valuable computer resources. Hence it is best that each sequence be played back at the users command. For example, the animation sequences could be played when the mouse cursor is placed over the icon as in the pop-up help note but doing so could obstruct the animation. The alternative could be to have the animation sequence executed through the right button mouse click on the selected icon.

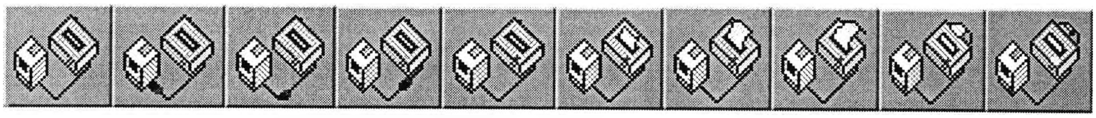


Figure 6.13 Animation sequence of a printer icon

In an experiment by Baecker et al. (1991), static icons were compared to animated icons on novice, familiar and expert users. All test subjects gave a higher subjective rating to the animated icons. Additionally, all the animated icons used in the experiment were understood by the test subjects, unlike some of their equivalent static icons.

6.8.3 Auditory Icons (Earcons)

Earcons are the addition of sound to graphical icons. It provides an alternate channel through which computers could communicate with users. In the author's opinion, the use of sound in icons (earcons) falls into a similar taxonomy to graphical icons but instead of being a visual representation, it is audio. Hence, the audio taxonomy of auditory icons falls into the same categories of representational, symbolic and sign earcons as do graphical icons. Representational sounds will sound like the sound caused by a real object that produces the sound. For example, an application being disposed off into the trash can of a Windows 95 GUI could produce a clanging sound as if a hard object had been dropped into a metal trash can. By making the model world (desktop) of the computer consistent in its visual and audio representation reinforces the "look and feel" or direct manipulation of an application (Hutchins et al., 1986).

The percentage done status bar commonly encountered in today's installation programs could, for example, include the sound of a container being filled with a liquid during the installation process. This sound usage falls into the symbolic category as the sound used is not a direct or representational sound of the object or action represented. The use of arbitrary pitch, volume, timbre and duration in producing sounds in earcons however falls into the sign earcons category. As computers are artifacts in which events do not always map neatly to the events in the everyday world, such sign earcons may have to be utilized at the interface.

As with graphical icons, the best sound to use will start with the representational sounds and when one cannot be found, symbolic sounds should be considered. Sign sounds should be the last resort as such sounds are not obvious immediately and have to be learned. The use of arbitrary sign sounds, however, are effective in conveying multidimensional, logarithmic or time-varying data (Bly, 1982; Mansur et al., 1985). Referring to Figure 6.1 for example, the first animated icon (CPU used) below the "Exploring" file manager window could use varying pitch in conveying how much of the CPU is being utilized while using a computer. The use of sound in this circumstance however, should be optional to the user as it could be irritating when such information is not required. In general, using natural sounds should provide a higher degree of articulatory directness than manipulating dimensions of the sound itself (Vanderveer, 1979). In the words of Gaver (1989), "people do not seem to hear sounds, but instead sources of sound". This means that people do so much listen to the dimensions (pitch, timbre loudness etc.) of sounds as to what everyday sound producing events was actually heard.

In some applications, audible clicks are heard when on screen buttons are depressed. With on-screen buttons, audible feedback sounds are commonly accompanied with a visual feedback of the button being depressed, thereby reinforcing the action. Gaver's (1989) SonicFinder for the Macintosh, is the first application to employ earcons in GUIs. In addition to feedback earcons, Gaver also introduces how earcons could furnish users with information not otherwise available directly. For example, when an icon is selected in SonicFinder, the selected icon will produce a wooden sound, metal sound etc. depending whether the selected icon is a file or application respectively. Additionally, when the selected icon is dragged (moved), the frequency of the sound will depend on the size of the application. Low frequency sounds represents small files while higher frequency sounds represents larger files.

The two main advantages found in using auditory icons in the SonicFinder (Gaver, 1989) are the increased feelings of direct manipulation, and the flexibility and less attention-demanding interactions it offers. User satisfaction was also found to be higher with utilization of the SonicFinder with the Macintosh interface. As with graphical icons, families of earcons could also be built to improve on consistency and understanding and this is especially so with sign earcons.

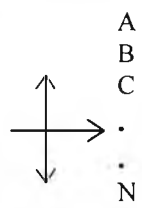
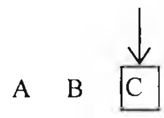
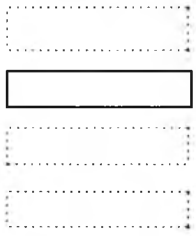
6.9 Iconic Evaluations

In using an icon, three elements are apparent as message, enabler and noise (Horton,1994). A message is what the icon is trying to convey, be it an object or concept that proposes its function. Enablers are any graphical elements in an icon that are not part of the message but do contribute to the efficient and reliable delivery of the message itself. Examples of enablers include backgrounds, consistent style, decorative touches, borders, guidelines and alignments. Noise is any element that does not contribute to being a message or an enabler, and hence interferes with the delivery of the message.

Noise in an icon can be detected by seeing the effects of its removal from the icon. If the removal of a graphical element in an icon improves on the efficiency and reliability of the delivered message, the graphical element is a noise. If however, its existence is found to enhance the message delivery, it is an enabler. In iconic evaluations, these are the three elements that designers has to consider. To create easy to understand icons, designers should encode critical messages redundantly, use enablers to enhance icon assimilation and eliminate any noise when found during testing.

Garcia et al. (1994) has devised a quantitative method (here referred to as the Garcia Method) of measuring abstractness based on the complexity of an icon. The metric value of an icon is calculated by adding up the number of the following components in each icon; closed figure, open figure, letters, special characters (excluding letters in the alphabet), horizontal lines, vertical lines and diagonal lines. In their experiment, Garcia et al. examined such Pascal constructs as Begin-end, Case, For, If, Repeat, While, etc. Different icons were proposed for each construct and their metric values calculated. These icons were then ranked into levels of abstractness by a group of subjects and then compared to the rankings using the metric values of each icon construct. The largest metric value for each construct is represented as being the most concrete while the least to be the most abstract. An example of the Pascal Case construct used by Garcia et al. in their experiments are shown in Table 6.7. The overall results of the experiments showed that the metric did function as a good quantitative measure; matching the subjective interpretation of abstract icons well, and of concrete icons moderately well.

Table 6.7 Metric Values of icons used by Garcia et al. in representing the Pascal Case construct

Pascal Construct	Icon A	Icon B	Icon C	Icon D
Case				
Metric Value	10	6	5	4

Two things can be observed about the icons used in Garcia's experiments. First, they represent concepts rather then concrete objects. Second, the graphical representations of their icons are simple (with metric values < 12) in comparison to today's icons, which often are complex and use colour. The question is whether the Garcia Method can be applied to current icons?

In the author's opinion, the Garcia Method should strictly be applied to graphical elements that represent conceptual ideas, very much like those in the reported experiments. The author suggests that more concrete representations have to be analyzed from a different perspective to the basic graphical elements proposed by Garcia et al., for two main reasons. Firstly, with the Garcia Method; the larger the metric value of an icon, the more likely it is to be understood (concrete). This principle is in contradiction with other research findings (Byrne, 1993), that states; for icons to be effective aids to a visual search, they must be simple and easily discriminable. The quantitative measurements worked with Garcia's (1994) experiments, because the icons tested did not have metric values exceeding twelve. With today's icons, Garcia's principle of a higher metric value representing concrete icons, will not hold as there will be a limit beyond which the icons will be seen as being too complex and ineffective.

Secondly, Garcia et al. found that grouping graphical elements as a single metric value was why some lower metric value icons were found to be more concrete than their higher metric value counterparts. Again, with current icons, this grouping of graphical elements appears more frequent, due to their complexity and hence it would be more difficult to isolate their effects on the metric values calculated. In the opinion of the author, the Garcia Method may still benefit some of today's symbolic icons in their determination of abstractness. However, the author proposes the use of the Garcia Method be followed by testing on typical users, and that its usage should be viewed as a guide rather than a rule.

6.10 Conclusion

Study of past iconic taxonomies, show that they have not changed considerably since 1955, the starting point. They generally fall into three categories of representational, symbolic and sign icons. The study of icons itself, can be divided into three broad areas, syntactics, pragmatics and semantics. Syntactics refer to the physical qualities of an icon while the pragmatics deal with how icons are produced and depicted. These two areas define the appearance of an icon. Semantics, however, refer to the meaning of an icon, which is dependent on the viewer's mind and any context that might exist.

Ambiguity in icon interpretation can be narrowed through using, where possible, more representational and contextually correct icons. The only way to determine the final meaning taken by users, however, is through user testing. Not every user will come to the same conclusion when it comes to the meanings of icons, but the most probable meaning can and should be taken to be the most suitable icon. A contextual object selection methodology for icon design is proposed, based on the extension of Kaneko's et al. (1991) object selection rating methodology.

In designing graphical representations for icons, preference should be given to graphical representations in the following order; representational, symbolic, and then sign icons. Representational icons can depict a subject directly, analogies, or metaphors. Depicting a subject directly is straight forward; analogies can be based on functionality, end results, structural analogies or body parts in action; and metaphors could come under various forms of synecdoche, litotes, hyperbole and euphemism. Symbolic icons are a little harder to portray, as it relies on depicting a concept rather than on objects. An effective symbolic icon focuses on the property of the image that carries the intended concept, often achieved through the use of a hyperbole. The uses of sign icons are not recommended due to their arbitrariness in meaning. However, when there are well-learnt signs in the target audience, the reverse is recommended.

To improve the efficiency of search times; icons should be designed with strong 'global' features as shape, and colour. Additionally, icon designs should reduce any complexity, as simplicity is critical to rapid location of icons. Table 6.2 provides some guidelines to the maximum number of codes for effective human differentiation. To further enhance iconic understanding, the use of help techniques, animation, and sound (earcons) to communicate functionality, properties and actions were also investigated. Finally, a recent quantitative methodology (Garcia et al., 1994) on iconic evaluations was investigated as to its suitability in evaluating iconic abstractness in icons today. The method was found to be unsuitable for representational icons. However, it may still benefit some symbolic icons in their determination of abstractness.

The next chapter investigates the subject of HMI screen design, which is based on how the designed icons (building blocks of an interface) are arranged in a 'Window' or screen, to produce a more effective, and attractive interface.

7. HMI Screen Layout Design

7.1 Introduction

In Chapter 3 (HMI Models and Design), the visual representation and aesthetics of an application were attributed about 10% substance of the designer's model (Section 3.4). This does not mean that the relevancies of screen design are any less important to the other two parts of interaction and object relationship. On the contrary, the visual representation, like the other two parts, plays a major role in the acceptability of an application. The three individual parts that go towards building the designer's model, can never stand alone, and the success of an interface depends on each of these three parts fulfilling their role.

This chapter concentrates on the visual aspects of an interface, while Chapters 3 and 4 concentrated on the object relationships and interaction of an application. The chapter starts by providing some empirical evidence to support the importance of screen design in HMI. It then goes through screen design properties that the author believes to be essential to the development of effective interfaces. Documentation on HMI guidelines and their effectiveness in aiding the design processes of user interfaces are studied. More recent advances in computerizing HMI guidelines using artificial intelligent (AI) technology are also investigated. Finally, the author proposes a practical method of incorporating screen layout design guidelines into the design process.

7.2 Importance of Screen Design

The presentation of subject content on visual displays will usually have a substantial impact on the user-friendliness and efficiency of interaction. Empirical studies on screen design have made this affirmation, time and time again. In a study by Tulis (1981), for example, redesigning the key display for a system that tests telephone lines resulted in a 40% reduction in the time required to interpret on-screen information. In another study that examined over 500 displays of airline or lodging information, the time taken to extract information from the worst designed screen was found to be 128% longer than from the best designed screen (Tulis, 1984). Other researchers have also made similar findings of improved performance in response time with the redesigning of screens. For example, Keister and Gallaway (1983) found that redesigning a series of screens for a software package, resulted in a 25% reduction in transaction time, 30% less data entry time and a reduction of 25% in errors. Burns, Warren and Rusidill (1987) found that by redesigning screens for the space shuttle, resulted in 30% reduction in search time for non-experts, but found no change for experts.

7.3 Screen Density

Besides screen layout, screen content density is often found to be one of the major determining factors of user performance in interpreting a screen (Callan et al., 1977; Dodson & Shields, 1978; Treisman, 1982; Tullis, 1984; Thacker, 1987). Dodson and Shield (1978) for example, examined Spacelab screen densities with 30%, 50% and 70% overall densities. With each increase in overall density, significant increase in search time was found. Similar response times were encountered in Thacker's (1987) study that compared screens with overall densities of 14%, 29% and 43%. In the study, a much larger search time was encountered when moving from the 29% to the 43% overall density screens. Increased error rates were also found with each increment in screen density, with the largest density showing significantly more errors.

Typically, there two types of screen densities that are calculated for a display, overall and local. Overall density, as mentioned above, determines the proportion of display characters with respect to the whole screen. Local density however, determines the concentration of characters within a group, which often occupies part of a screen. Tullis (1983) has written a program which automatically determines such groupings, along with a variety of techniques for analyzing screen formats. The measure of local density derived by Tullis is the percentage of characters in a 88-character visual acuity circle, modified by the weighting factor illustrated in Figure 7.1. The visual acuity circle used in Tullis' local screen density calculation is based on the eye being most sensitive at 5-degrees of visual angle (Figure 7.1). In his 1983 study, Tullis found a redesigned screen with a lower overall and local densities to be more effective. Additionally, a lower local density was found to be the more important factor in creating an aesthetically pleasing screen display.

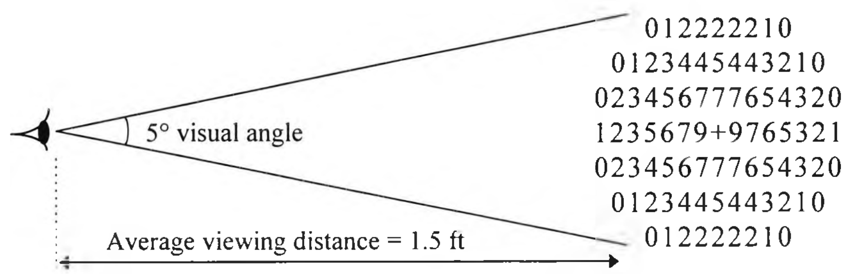


Figure 7.1 Tullis' weighting factor in a 88-character visual field acuity circle

In a follow-up study, 52 different screen formats were analyzed by Tullis' (1984) program. The examined display formats varied in many parameters, including overall densities ranging from 10% to 58%. Again, search time was found to increase with increasing density. The low correlation coefficient (r^2 = 0.33) of search time versus screen density, achieved in the experiment, however, indicated that other factors besides overall density, had an effect on search time. In the study, search time was found to increase with the number of groups or the average group size. For groups that were smaller than 5 degrees of visual angle, search time was primarily a function of the number of groups, while for those screens with groups larger than 5 degrees, the search time was primarily a function of the size of the groups. The recommended maximum screen density, for alphanumeric displays is about 25% to 30% (Tullis, 1981).

Referring to how these densities are calculated, empirical studies on the effect of screen density on user performance thus far, relate to alphanumeric displays. However, the author suggests that a measure of screen density for graphical displays, if one can be measured, would produce similar results. Practically all guidelines on screen density state that the total amount of information to be displayed should be minimized by presenting only what is essential to making a decision or performing an action (Smith & Mosier, 1986; Brown, 1988; Galitz, 1993).

The effects of screen density on user performance, also falls back on the fifth principle of HMI psychology (Chapter 2), which is based on the limitations of human memory. As previously stated, Miller (1956) puts an optimal limitation number of seven, plus or minus two 'chunks' of information on human working memory. This limitation generally applies to situations where users are expected to monitor or control a process or a number of processes. It is in these circumstances that the number of elements to control or monitor should be reduced to meet the limitations on human working memory.

7.4 Screen Design

Screen design is a combination of art and science. The many guidelines offered in HMI standards and guidelines today, are mostly based on the collective thinking of behaviorists and the experiences of designers, rather than on empirical studies. Even though the number of empirical studies on HMI is growing (see Smith & Mosier, 1986), its research has a considerable way to go towards establishing a mature understanding of the subject. Furthermore, most empirical studies on HMI are still based on the old alphanumeric display types, rather than the more common GUI displays found today. Nevertheless, many of the empirical studies on alphanumeric displays can be generalized for graphical applications.

Documentation on HMI design guidelines have grown in considerable numbers in the last decade. These can be categorized into three types, each meeting a different HMI design requirement. The first category deals with guidelines on alphanumeric displays, which currently has the largest amount of documentation based on empirical studies. The second category is based on guidelines for GUI interfaces. These, however, are often extensions of the first category but with the inclusion of guidelines for graphical elements in a GUI interface. The final, third category, is based on standards and styles, commonly found for the more recent WIMP (Windows, Icons, Menus & Pointer) interfaces. Examples, include IBM's System Application Architecture:

Common User Access (1987); Apple's Human Interface Guidelines: The Apple Desktop Interface (1987); Sun Microsystem's OPEN LOOK Graphical Interface Application Style Guide (1990); Microsoft's, The Windows Interface: An Application Design Guide (1992). The main purpose of style guides is that applications developed for a specific environment are consistent across different applications.

To give an impression of the extensiveness of some of these design guidelines, the author has prepared a summary table (Table 7.1). The table gives the number of guidelines and breath of topical coverage, taken as an example from each of the design guideline categories previously covered. It was difficult to define the number of guidelines provided by the Microsoft Style Guide, as these are not provided on a point-by-point basis, but are imbedded in paragraphs of text, tables and graphics. Their categories were also difficult to establish, as there were many style guides, some of which are very detailed. It was not clear as to whether they should be counted as a single guideline or a separate few. The author, however, believes that the figure runs into the hundreds, at the very least. The figures in Table 7.1 is only the beginning, as they are increasing in number, year by year.

Table 7.1 Sample number of guidelines and coverage of the three different categories

Category	Major Topics	Number of Guidelines
First Category -	Data Entry	199
Alphanumeric Interfaces :	Data Display	298
Guidelines for Designing User	Sequence Control	184
Interface Software,	User Guidance	110
by Smith & Mosier (1986).	Data Transmission	83
	Data Protection	70
Total Number of Guidelines		**944**
Second Category -	Considerations in Screen Design	155
GUI Interfaces :	Data Entry Screen	131
(inc. alphanumeric guidelines)	Inquiry Screen	56
User-Interface Screen Design,	Menu Screens	97
by Galitz (1993)	Graphical Screens	371
	Iconic Screens	18
	Statistical Graphics	70
	Colour	80
Total Number of Guidelines		**978**
Third Category -	Fundamental Input Devices (Mouse & Keyboard)	
Standard or Style Guide :	General Techniques (Interaction Methods)	Large number (>100's)
The Windows Interface:	Windows	
An Application Design Guide	Menus	
by the Microsoft Press	Dialog Boxes	
Total Number of Guidelines	In the hundreds, at the very least. ←—	?

As the number of guidelines in recent years has grown to such an extent, research is now being performed to investigate how well guidelines are being followed. Such findings, have not been very promising, as written guidelines and style guides have often been found to be difficult to access and interpret. Smith and Mosier (1986) for example, found that 36% of designers had trouble looking for specific guidelines when using a large interface guideline document. In another study, 90% of designers had trouble interpreting a set of guidelines, given for a design task (de Souza & Bevan, 1990). In yet another study, a company's screen design standards were found to be violated 32% to 55% of the time (Thovtrup & Nielson, 1991). In their study, they found that designers depended heavily on the pictorial examples provided in the documentation guideline, often ignoring the accompanying text. Pictorial guideline representations are often faster and easier to understand, as they distinctively demonstrate the context in which the guideline applies.

In recent years, some of these design guidelines have started to appear in software format. Design guidelines that are available on-line have the added advantage that they may be applied in an interactive and dynamic manner, as oppose to paper-based material. Cross referencing, indexing and searches are much quicker on the computer, especially for reference materials. The incorporation of artificial intelligence (AI) however, brings this a stage further in the employment process of computerized screen design guidelines. Research in the employment of knowledge based critiquing systems is underway and showing great potential for their incorporation within traditional software design processes (Löwgren & Laurén, 1992).

Löwgren and Laurén have developed and tested their second generation critiquing system called KRI/ AG. KRI/ AG is based in part on Smith and Mosier's (1986) guidelines (60 in all) and in part on the MOTIF style guide (40 in all). KRI/ AG is able to evaluate user interface designs submitted to it in the MOTIF interchange language by providing it in a textual evaluation report. In one of their studies, the system was tested on four commercial designers (Löwgren & Laurén, 1993). The result demonstrated the system's ability of catching mistakes and oversight on the part of the designers in meeting the MOTIF style guide and following Smith & Mosier's (1986) guidelines. Style guide compliance is becoming increasingly important in the software industry. Therefore, such knowledge based systems as the KRI/ AG system is becoming indispensable.

Besides direct references to some of the HMI design guidelines discussed, other sources that can assist in screen design come from the media world, such as television and advertising. In advertising for example, Nelson (1981) describes five basic principles of design: balance, proportion, sequence, unity and emphasis.

A balanced design should not be confused with a symmetrical design. In a symmetrical design, objects are placed in a mirror image fashion to give an impression of balance. Symmetrical design is shunned by the media industry as being ordinary and dull. A well balanced display, however, creates the feeling of stability and confidence in the viewer, while an unbalanced display creates a feeling of stress. The latter is sometimes desirable, often used to show dynamism in moving objects for example. Proportion is a comparative relationship between objects in space. This can be made in terms of size, depth, line thickness, boldness, degree of shading, colour, etc. and are used to show contrast. In photography, good proportions are commonly achieved by the golden 'rule of thirds', a trick often taught to novice photographers. Instead of placing the main object in the center of the frame, the rule of thirds states that main objects should be placed among the various thirds of the frame. Sequence dictates the path taken in observing objects in a display. A flowing motion of the eyes in viewing a display is desirable rather than a staccato motion. The latter motion brakes up viewing and observers get lost in the display. Observation becomes haphazard in fashion. Unity dictates that elements on a display should blend together and appear unified. Elements in different part of a display can be related to each other by issuing the elements with similar borders, colour, size, shape, texture, etc. Emphasis is used to make objects stand out in a display. In advertising, objects to be advertised are usually emphasized, drawing the attention of viewers to the object.

7.5 Practical Screen Layout Design Principles

The author has identified four main principles for screen layout design, with an aid to memory as 'PRACtical'. This stands for Proximity, Repetition, Alignment and Contrast.

7.5.1 Proximity

The basic purpose of *Proximity* is to organize information on a display. Perceptual psychology states that the closer the proximity of elements are to one another, be it in space or in time, the greater is the tendency to group the elements together as a unit (Section 2.3.1). However, unrelated objects can still be placed in close proximity, giving it the impression of being related. So the key here is using proximity to organize related objects.

Organization provides some form of sequence to what is observed. For example, if icons were displayed all over a screen in a haphazard manner, as in Figure 7.2; observers would not know where to start looking and where to end. Observe how the eye jumps from one icon to another in almost a random fashion when viewing Figure 7.2. Also observe how the effect of placing icons next to each other or in close proximity, gives the impression of unrelated icons belonging together.

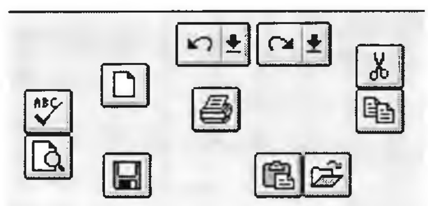


Figure 7.2 Random arrangement of icons

The arrangement of the icons just below the menu bar in most windowing application found today, organizes the icons in a horizontal order. Figure 7.3 shows the toolbar from Microsoft Word for Windows 6.0 (WinWord). Most Western observers would look at the icons in turn from left to right. This comes from the habit of reading from top left to bottom right. Likewise, items further up a screen will probably take more prominence than that further below. Proximity is used here effectively, to organize related functions into groups. For example, the first three icons in group A represent functions concerning the whole document. The first icon represents 'create' a new document, this is depicted by a clean sheet of paper; the second icon represents 'open' a document, and the third 'save' the current document. Group B is for 'verifying' the document and 'printing' it. Group C is for editing the text in the document, like cut and paste, etc. and Group D is for 'undoing' and 'redoing' a mistake.

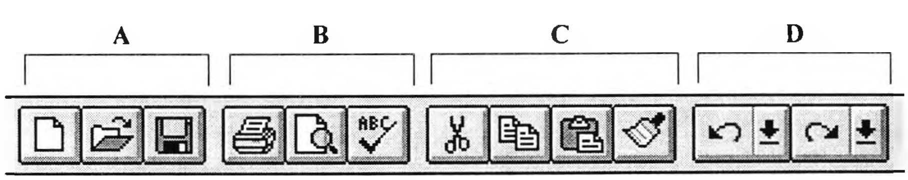


Figure 7.3 A toolbar from Microsoft Word for Windows 6.0

Observe, the effects of leaving equal amounts of space between groups of elements in Figure 7.3, causes the grouping to appear to be a subset. In this instance, it is desirable, as all the grouped icons in Figure 7.3 are a subset of the toolbar. However, unintentional use of spaces could clearly have detrimental effect.

Too many groups in a display can reduce the amount of spaces surrounding a group. This reduces the effects of proximity and makes the display appear too cluttered and unattractive. Where possible, especially in crowded displays, the number of groups should be reduced to no more than about five. For example, WinWord reduces clutter on its display by allowing its users to turn off the display of unneeded toolbars.

7.5.2 Repetition

The purpose of *Repetition* is to unify and to add interest to a screen display. Unity of separate elements or groups of elements on separate screen displays can be acheived by repetition of features. Functional repetition forms a system of visual and structural elements that give the basis for a family of related items. The multimedia application, 'The Animals!' by Software Toolworks (Figure 7.4) demonstrate the effectiveness of repetition in unifying separate screens while adding aesthetic interest. The clickable images on the main screen are highlighted in a red rectangle when the pointing cursor is placed over it. These clickable montages reappear as backdrops in the topic screen selected, as can be seen in the two screen snap shots shown below the main one. This repetition aids the user in the navigation throughout the exploration of the animal kingdom. Parent-child relationships among the elements are used effectively here to represent the hierarchical relationships among the screens. The user knows at any stage their whereabouts, a feature that adds confidence.

In studying Figure 7.4, further repetition or consistency can be found in the navigational bar at the top of the screen, position of topic title, position of buttons lining the bottom of the screen, placement of photographs and textual information. The use of colour and texture is also consistent.

Repetition helps organize information; it helps guide users through the screens; it helps unify disparate parts of a design. Even in a single screen, repetitive elements establish a sophisticated continuity. In multiple screens, the use of repetition is essential to the success of a design.

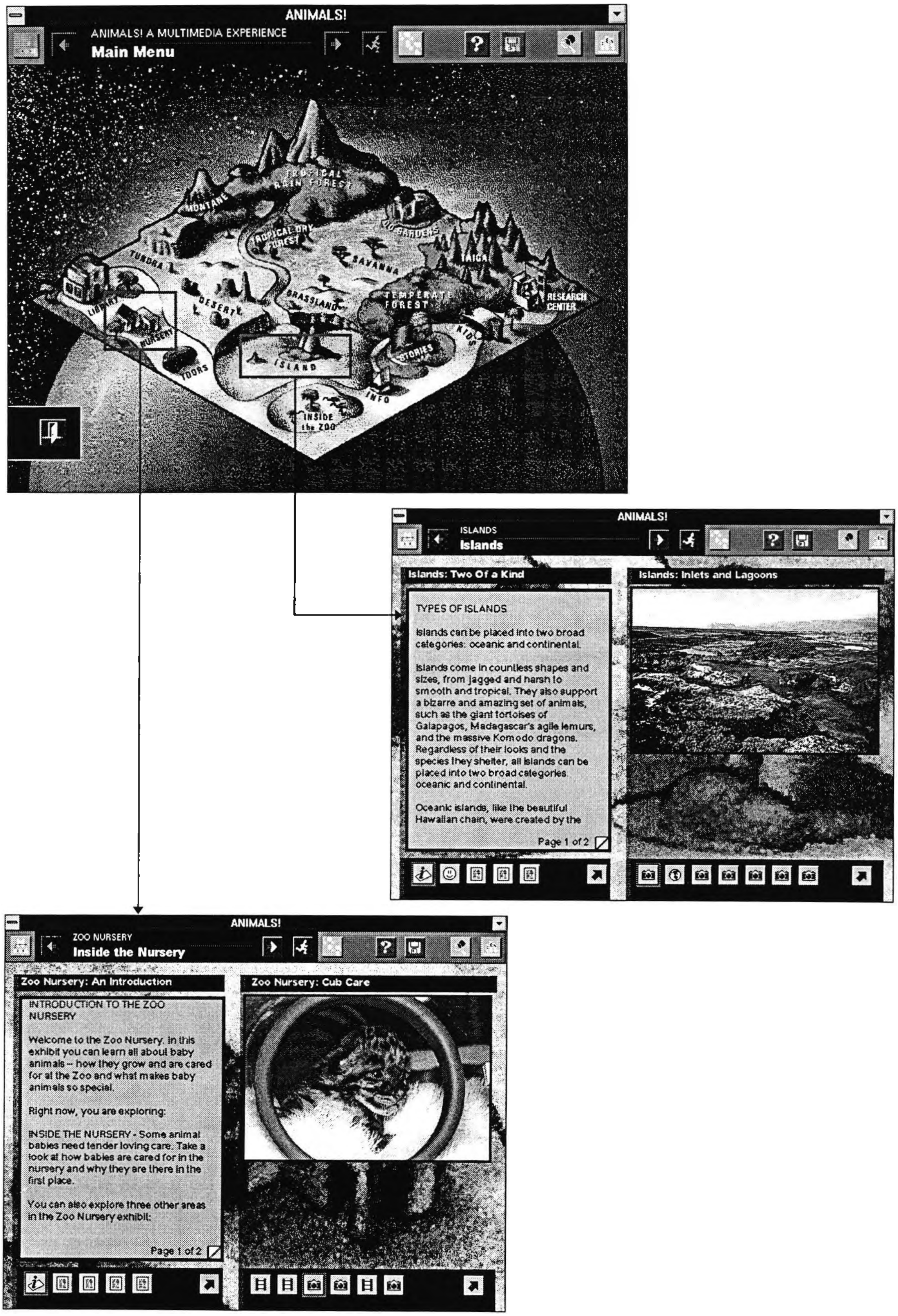


Figure 7.4 Screen snap shots from 'The Animals!' by Software Toolworks

7.5.3 Alignment

The *Alignment* principle states that nothing should be located in an arbitrary manner. Every element placed on the screen should have a visual connection with something else on the display. The purpose of alignment is to unify and organize elements on a screen. Alignment can also add structure to an otherwise confusing screen and give it a well proportioned appearance. Figure 7.5 shows a reproduced version of the 'Inside the Nursery' screen snap shot from Figure 7.4, but with guidelines in place to show the alignments used. Figure 7.5 would look better, if the photograph on the left of the text area was aligned with the top of the text border, though the author believes that it was the intention of the designer.

Figure 7.5 Effects of Alignment on screen design

Alignment is able to unify items on a screen even if they are do not have close proximity to one another. For example, take the row of push buttons at the bottom right of the diagram in Figure 7.5. The single push button on the far right is spaced some distance from the rest, but yet still maintains a relationship with them. Part of the reason is because it is aligned with the other buttons. The relationship here is also reinforced by having them in a repeated colour and having all the buttons fit within the same black rectangular area.

Consistency of alignment is very important in multiple screen applications. If elements in a screen display where not placed in an identical position in a multi-screen application, the elements will appear to jump when moving from one screen to another. This effect is highly undesirable and can be eliminated by using consistent gridlines in the development of an HMI.

Alignment in screen displays, however, are not always essential, especially in the design of HMIs that depict objects in the real world as in Figure 7.6. But even in these environments, elements or objects should still not be placed in an arbitrary manner. Objects should be placed in such a way that it leads the eye through all the important objects in a fluid manner. The reader is invited to examine Figure 7.6 and make a conscious note of how the eyes goes through the various objects in the scene.

Figure 7.6 Startup Interface for the Hutchinson Encyclopedia

Figure 7.7 Flowing motion of the eyes through the objects

Figure 7.6 uses various methods to captivate the users attention and to guide the user's eye through each objects in turn, hopefully in the sequence planned by the designer. The objects in the scene are almost laid in a circle (Figure 7.7). This has the effect of leading the eye through a circular motion through the various objects. The direction of flow could go in the clockwise or anti-clockwise direction. Most users, however, are accustom to the clockwise direction. Note the depiction of Figure 7.6 may not demonstrate well the points the author is about to make, as it is in gray scale print format.

The starting point of the visual scan will probably start with the brightness object in the scene, this being either the table lamp, the hour glass or the open book. As the table lamp does not bring any initial significance to an encyclopedia, nor the hourglass, the user is more likely to start with the open book. This starting point is further affirmed by placing the book open in the foreground.

The shimmer of the table lamp and hour glass will probably re-attract the user's attention. Following this, the user might browse through each object. However, some users might not be attracted back to the table lamp or hour glass. Instead, some users might refer to the objects in the foreground, hence, making them scan in an anti-clockwise fashion. Either way, both routes meet the requirement of the designer in having the user browse through each object in the scene, while starting with the most common starting point, the browser. The circular arrangement of the objects in the scene creates an infinite browse route, keeping the user's attention on the scene for as long as possible. These are a few visual techniques use to control the user's eye, and to keep attention.

7.5.4 Contrast

Contrast adds visual interest to a display because it draws the observers attention. For contrast to be effective, it must be strong. For example, it is ineffective to contrast 12-point type with 14-point type, as most observers will not be able to tell them apart in the first instance.

Contrast can be created in many ways. It can be achieved by combining large elements with small elements, thin lines with thick lines, foreground elements with background elements (see using depth perception, in Section 2.3.3), warm colour with cool colour (see Chapter 7), brightness with dimness, rough texture with smooth texture, bold type face with normal typeface, etc. In some instance, the latter might also require that the bold type face be made 2-point type up in font size.

Contrast can also create an organizational hierarchy among different elements. Perceptual psychology has shown that observers move from large objects to small objects, from bright colours to subdued colours, from irregular shapes to regular shapes, and from moving objects to static objects. Organizational perception can, and often is, used to achieve a hierarchical organization. An example on using contrast to aid in the visual path on a screen display was demonstrated in Section 7.4.3, which makes reference to Figure 7.5. In this example, contrast between brightness and dimness and between foreground and background were used.

7.6 Conclusion

The effects of screen design on user performance has received considerable attention in the study of HMI. Most empirical experiments on screen design have demonstrated their importance in producing effective HMIs. Besides screen layout, screen density is often found to be one of the major determining factors of user performance in interpreting a screen. Practically all research into screen density has indicated that user response time generally gets longer with increased screen density. For alphanumeric displays, for which most research into screen density has been conducted, the recommended maximum screen density is about 25% to 30%. Miller's (1956) magical number of seven, plus or minus two chunks of information, could also be used as a restraining factor to screen densities. This limitation generally applies to situations where users are expected to monitor or control a process or a number of processes. It is in these circumstances that the number of elements to control or monitor should be reduced to meet the limitations on human working memory.

Documentation on screen design guidelines is increasing in number and the number of guidelines within them. This has caused considerable concern on their usage. Research findings on this have not been very promising so far, as written guidelines and style guides have often been found to be difficult to access and interpret. Computerizing screen design guidelines have helped improve their usage. Furthermore, the incorporation of knowledge-based technology to create a critiquing system has been shown to vastly improve how current design guidelines are being used. As these knowledge-based systems are still non-commercial, the author has created an acronym to assist screen layout designers incorporate the basic design principles into their screen designs. The design principles are embedded into the first four characters of the word 'PRACtical.' They stand for proximity, repetition, alignment and contrast.

The following chapter begins discussion on Part 2 of this thesis, NDT covermeter automation.

8. Covermeters

8.1 Introduction

Covermeters are battery operated devices, their size being small enough for easy portability as necessary for on site use. Covermeters are used to locate the position and orientation (usually) of reinforcing bars in concrete, to measure their depth of concrete cover and to provide estimation of their sizes. The various methods for estimating re-bar sizes are discussed in the Chapter 9.

The objective of this chapter is to introduce readers to covermeters. It includes discussion on their role in the inspection process, the principles involved in their operation, the different head designs found in some commercial covermeters, and a discussion on their expected accuracies under various site conditions. Discussion is also given on new features to be found in some of today's covermeters. As a CM5 CoverMaster covermeter (Protovale (Oxford) Ltd.) is used in the experiments described in Chapter 10, an in depth coverage on it is provided in this chapter. The various methods of locating and estimating depth-of-covers, using the CM5 covermeter is also described.

The chapter ends by providing a discussion of the potential of employing a knowledge based system to the inspection process of a covermeter.

8.2 Importance of Cover Determination

Covermeters are a commonly used NDT device in the construction industry. This is to no surprise, as the location and size of reinforcing bars (re-bars) are vital to the determination of the strength and durability of reinforced concrete structures. If re-bars are displaced in the concrete casting process, with the depth-of-cover reduced below that specified, structural cracks may occur that are likely to cause corrosion of the reinforcing bars. The corrosion of the reinforcing bars can further cause spalling or delamination and hence, weakening the structure. Spalling is caused by the expanding rust first splitting, which then leads to the pushing of the surrounding concrete and finally to the detachment of part of the concrete cover. Delamination, alone, is worse, in that the process is usually non visible and the damage usually far greater. Here again, the process starts by the growing rust originally splitting, but this time the splitting occurs in a plane parallel to the re-bars. In time, the rust grows enough to detach the cover in large sheets.

8.3 Covermeter Principles

The basic principle underlying a covermeter is that an electromagnetic field is applied at the surface by a search probe. From an assessment of the effects or distortions of this field by the presence of reinforcing bars, deductions can be made on their depth of cover and sizes. The interaction of the probe head coil with the reinforcing bars is due to either or both of two physical properties of the re-bar; its magnetic permeability and its electrical conductivity. Instruments that measure the magnetic permeability of re-bars are said to apply the magnetic reluctance technique and instruments that measure the electrical conductivity of re-bars apply the eddy current technique.

8.3.1 Magnetic Reluctance Technique

The first covermeter was developed in 1955 (Alldred, 1993). The technique involves the use of magnetic reluctance, similar to that of a transformer, in that one or two coils are used to carry the driving AC current, while another one or two coils pick up the flow of magnetic flux via the magnetic circuit formed by the search probe and embedded reinforcing bar. This is analogous to the flow of current in an electrical circuit. Resistance to magnetic flux is called reluctance. In the absence of a re-bar, the reluctance of the circuit is increased due to the high reluctance of the concrete that forms the complete circuit. In the presence of a ferro-magnetic re-bar, the reluctance drops and hence an increase in output is perceived by the monitoring coil. The maximum signal is achieved when the search probe is aligned with the re-bar and the signal increases slowly with the increment of bar size and decreases rapidly with distance (cover). This technique however, is very susceptible to variations in temperature in the core of the search probe, external magnetic fields and possible magnetic aggregates in concrete.

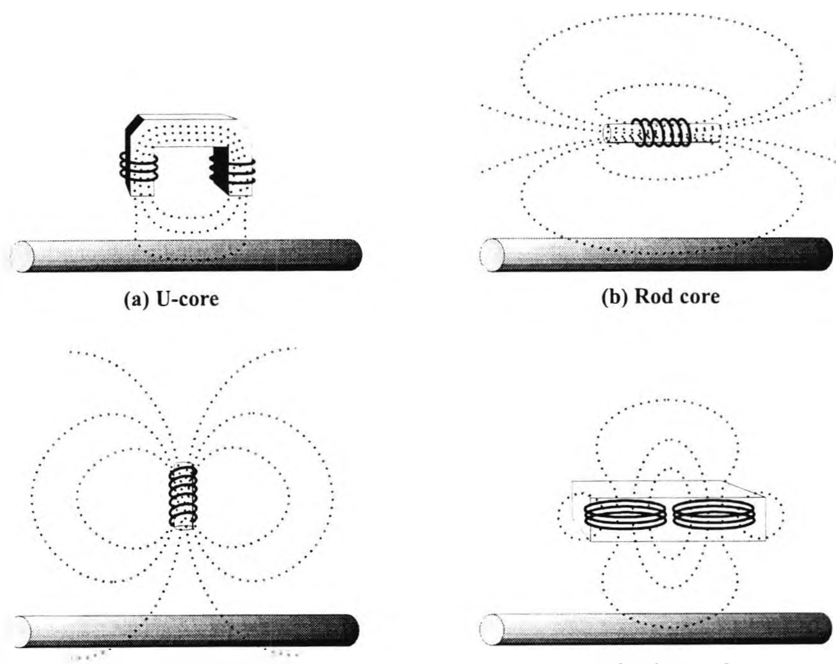
8.3.2 Eddy Current Techniques

If a coil carrying an alternating (AC) current is placed in proximity to a conductive material, secondary or eddy currents will be induced within the material. The induced current will produce a magnetic field in opposition to that which produced it, hence causing a change in the measured impedance of the search coil. The presence of a re-bar is inferred by monitoring the change in current flowing through the coil. There are two types of eddy current meters; one is based on the continuous excitation of the coil at frequencies above 1 kHz and the other is based on pulse excitation. The pulse excitation technique separates the received signal from the transmitted one, so there would not be any signal in the absence of a bar. Eddy current meters are more stable then magnetic reluctance meters and they are very sensitive to the presence of any conducting metal in it's vicinity. This technique may also be affected by non-magnetic conducting materials and are likely to be more susceptible to changes in reinforcing steel type than those based on the magnetic reluctance technique. Here again, the signal received by the search probe increases with bar size and decreases with depth of cover.

Other techniques used would in general be a combination of the above two techniques.

8.4 Head Designs

Search probe heads often come in two sizes, standard/ large for measuring average to greater depth of cover and small for shallower depths (< 30mm). Some known designs are as follows (Alldred, 1993):-



(a) U-core (b) Rod core

(c) Vertical coil (d) Air-cored

Figure 8.1 Various internal designs of covermeter heads

8.4.1 U-core

The U-core is the first design used for a covermeter, and is still found in some of the older covermeters available today (Figure 8.1(a)). U-core covermeters employ the magnetic reluctance technique. The U-core probe produces a directional, well-controlled field distribution but lacks stability. Examples of covermeters which employ the U-core design include the analogue Fe-Depth covermeter and the newer digital version, the Digicover from C.N.S. Electrics Ltd.

8.4.2 Rod-core

Rod-core (Figure 8.1(b)) offers deep penetration for greater depth-of-cover measurement in a modestly sized probe head. However, as its field strays all over the place, it is very susceptible to bar congestion, and is therefore very unstable. The Mk 6 analogue meter from Kolectric utilizes this design and so does the Profometer 2, a predecessor to Profometer 3 from Proceq. These rod-core covermeters employ the eddy current technique.

8.4.3 Vertical coil

Vertical coil (Figure 8.1(c)) generates a much tighter field and is hence very good at pinpointing the presence of re-bars. This design however, is non-directional, and therefore cannot determine the orientation of re-bars. The performance of this design degrades in the presence of welded meshes. Both the spot probe and the depth probe for the digital Profometer 3 covermeter from Proceq employ the vertical coil design in their search heads. This covermeter employs the eddy current technique.

8.4.4 Air-cored

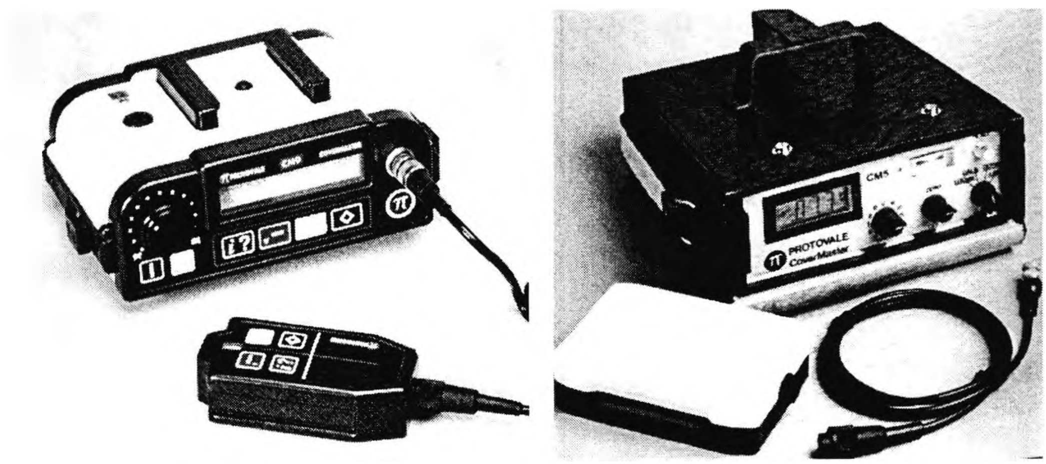
The air-cored (Figure 8.1(d)) head produces a field pattern very much like that for the U-cored heads but without the drawbacks of temperature dependency and produces consistent and stable results. Both digital covermeters from Protovale, the CM5 CoverMaster and the CM9 CoverMaster covermeters employ this head design. These air-cored covermeters are based on the eddy-current technique.

8.5 Covermeter Accuracies

All covermeter manufactures now claim conformity to the BS1881:Part204, “Recommendations on the Use of Electromagnetic Covermeters," which states that errors of no more than ±2mm or ±5% is allowed for a single bar under ideal laboratory conditions, ±3mm under favorable site conditions (BS4408:Part1) and ±5mm or ±15% accuracy under average site conditions. Most covermeters today do conform to the ±2mm accuracy under laboratories conditions however, the conformity to ±5mm accuracy under average site conditions with the effects of bar congestion is questionable.

8.6 Supplementary Covermeter Features

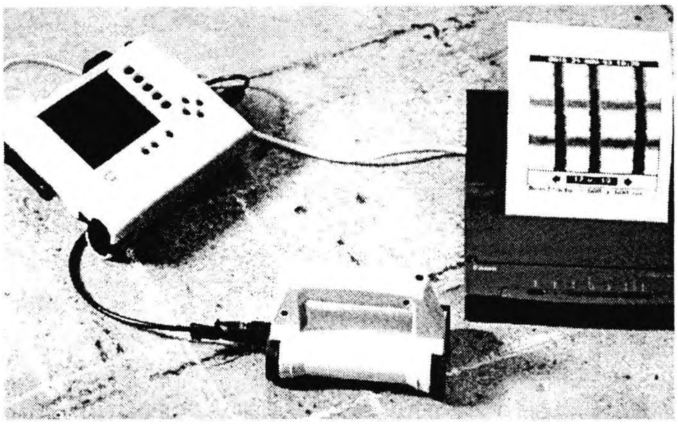
With older covermeters, re-bar size estimations often meant employing time consuming iterative methods (see the Spacer, the Spacer Ratio and the Orthogonal Methods of Chapter 9). More recent covermeters, however, have automated this process of re-bar size estimation. The CM9 covermeter (Figure 8.2(a)) by Protovale Ltd., for example; provide an automatic run time bar sizing feature. Two different techniques are employed, they are called "Autosize" and "Orthogonal". Another covermeter that provides a similar diameter estimation of re-bars, but this time using a spot reading is the Profometer 3 covermeter with it's "Diameasure" probe from Proceq (Promotional Brochure). The Diameasure probe also compensates for the effects due to magnetic aggregates and special cement.



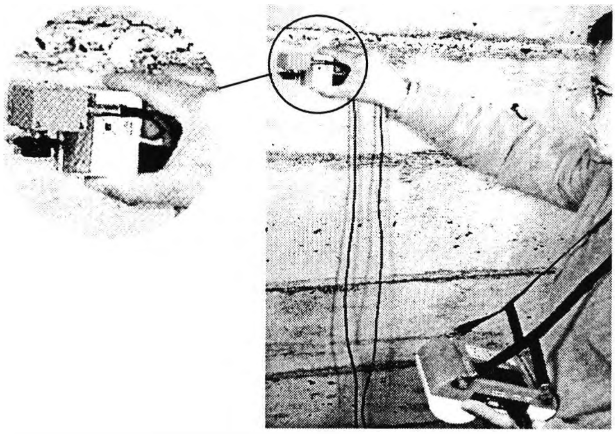
(a) CM9 Covermeter (b) CM5 Covermeter

Figure 8.2 Covermeters from Protovale (Oxford) Ltd

Some recent covermeters also have the ability to log data using a data logger. Both the CM9 and CM5 covermeters (Figure 8.2(a) & 8.2(b)) for example, have provisions for a data-logger. The CM9 covermeter is an update to the CM5. A step ahead of this, some covermeters provide a liquid crystal display (LCD) that displays a graphical image of the surface area under test. These covermeters use a wheel based displacement encoder to provide a position reading to each reading of the covermeter. The surface to be measured is scanned in the x and y direction with a mobile probe. An image is then produced on an LCD which give the position and orientation of re-bars. Cover can be shown as gray scale intensity or as numerical values in a spreadsheet format. Examples of devices capable of these outputs include the Ferroscan FS 10 system from Hilti (Gt. Britain) Ltd (Figure 8.3(a), Promotional Brochure) and the Profometer 4 Rebar Locator by Proceq SA (Figure 8.3(b), Promotional Brochure).



(a) Ferroscan FS 10 from Hilti (Gt. Britain) - Gray scale image of the re-bars is shown on the paper printout



(b) Profometer 4 from Proceq SA (Switzerland) - The operator is using a path-measuring device, an attachment to the search probe that makes re-bars visible on the LCD screen through an integrated CyberScan software

Figure 8.3 Two commercial covermeters with the ability to produce a gray scale representation of embedded re-bars

8.7 CM5 Covermeter

As much of the results in this project come from the use of the CM5 covermeter, it's details are covered herein. The CM5 covermeter first appeared in 1986. It is designed to operate in two main modes; to locate the position and orientation of reinforcing bars in concrete and to accurately measure the depth of concrete cover to the re-bar. In addition to this, there are various manual techniques available to estimate the sizes of re-bars where necessary (see Chapter 9).

The CM5 covermeter consists of two parts; a search probe and the main covermeter itself (Figure 8.2(b)). The search probe is a rectangular encapsulated unit containing air-cored coils which uses a pulse induction eddy current technique. The basic principle involves the use of a series of sharp pulses of current to produce a magnetic field in the transmitting coil. This process produces an intermittent production of magnetic field. At each interval where no magnetic field is produced, and if no conducting material is present; like a re-bar, no signal will be received by the search coil. However, in the presence of a re-bar, a current will be induced which in turn will produce a magnetic field around the re-bar that will be transmitted back to the search coil. This process of metal detection is very sensitive to small changes in voltage and is used very effectively to indicate the presence of metal. The advantage of this methodology over the more common continuous pass of current through the search head of other covermeters is stability. With the other designs, the presence of nearby metal is indicated by minor variations in the associated voltage. Temperature changes, electrical interference or magnetic interference like the earth's magnetic field can sometimes produce this variation, making this process less stable than the pulse method.

As the coil windings of the CM5 covermeter is directional, the search probe should be used with its long axis parallel to the expected line of the reinforcing bar being measured. For normal depths of cover (30 - 90mm) the black face of the search probe should be held in direct contact with the concrete, directly above the bar to be measured. For covers less than 30mm, the search probe should be turned over so that the white face is in contact with the concrete and 30mm subtracted from the indicated cover. For a more accurate analysis, a spacer can be used instead. For conventions used in this thesis, black face readings will be referred to as 'standard readings' and white face readings as 'spaced readings'.

The main covermeter unit is battery operated for portability. The left-hand side of the covermeter front panel consist of a LCD which gives a digital readout of either the signal strength or the depth of cover, depending on the mode of operation. To the bottom right of this LCD, are three knobs. The first is to set the bar diameter, the second to turn the instrument On and Off, by rotating clockwise. This knob also acts as a zeroing knob to calibrate the covermeter to read a zero value in the presence of any residual magnetic medium. The third is used to select from the modes of operation: LOCate, CALib (calibrate), Depth (cover) and +aud (cover with audio feedback). Above the zeroing knob, sits an analogue meter which gives a guide to signal strength and to the right of this, the socket for the search probe head. An illustration of the CM5 CoverMaster covermeter front panel is given in Figure 8.4.

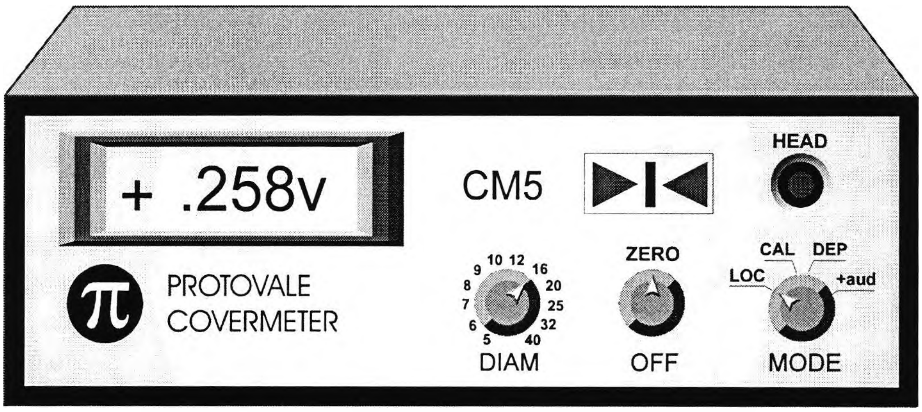


Figure 8.4 Front Panel of CM5 covermeter. Enhanced representation of Figure 8.2(b)

8.8 CM5 Covermeter Operations

Operational descriptions on the covermeter here is not exclusive to the CM5 CoverMaster covermeter and most, if not all, can be applied to covermeters of other manufacturers.

8.8.1 Locating the Position of Reinforcement Bars

For a single bar, the search head is placed in contact with the surface and moved over the re-bar with the head aligned parallel to the expected run of the bar until a peak signal is obtained. This is an indication of the position of the re-bar. Scanning from side to side of the bar is often necessary to obtain an accurate position of the re-bar. An illustrated example of the variation of signal strength against distance to a re-bar is given in Figure 8.5.

To detect the orientation of the re-bar, the CM5 head is rotated over the central axis of the re-bar until a peak signal is obtained. The orientation of the CM5 head at this point is an indication of the direction of the re-bar. The variation of signal strength against the rotational angle of the CM5 head with respect to the re-bar is very similar in shape ("bell shape") to that shown in Figure 8.5. Peak signal is obtained when the head is aligned parallel to the re-bar, i.e. at 0° rotational angle and minimum signal is obtained when the head is perpendicular; i.e., 90° to the re-bar direction.

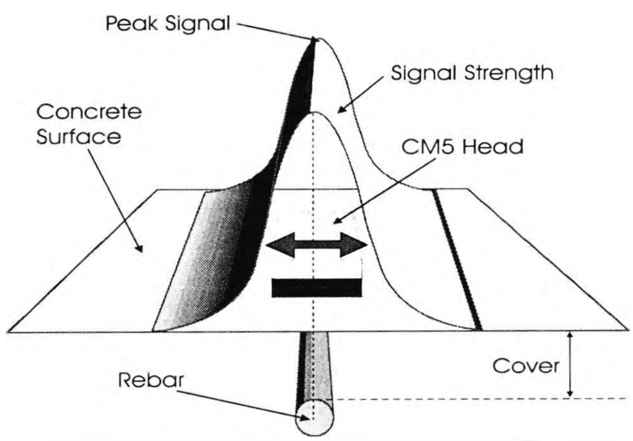


Figure 8.5 CM5 covermeter signal strength vs. distance from center of re-bar

The final step is to scan the re-bar in the lengthwise direction to determine the effects if any, of traverse bars and lapped bars.

In the case of multiple re-bars, the location of re-bars needs first be determined. The first step is to make an informed guess of the reinforced structure. If the two layers of reinforcement bars are of equal size, the top layer is first located, otherwise, the more predominant of the two. Next, the head is aligned to the chosen bars and a side-way scan performed, marking each maximum signal position on the concrete. Thirdly, the head is rotated to the initially chosen bars. A further side-way scan in between the markings of the first scan is carried out, again marking the positions of peak signal. The final result is an indication of the position and orientation of the detected re-bars. Cover, at each point of the markings can then be made.

In an isolated bar, eddy current is produced around the circumference of the bar but in a welded mesh, eddy current is also produced along the run of the mesh around the search head as in Figure 8.6. The difference in the eddy current pattern produced in the welded mesh is due to the electrical contact at the crossing point of each bar. This difference also leads to a different means of re-bar detection as peak readings are also achieved when the long axis of the head is perpendicular to the bar being measured, this being in contrast to the head being parallel for single bars. As usual, minimum reading is obtained when the head is in the centre of the space between bars, whatever the alignment.

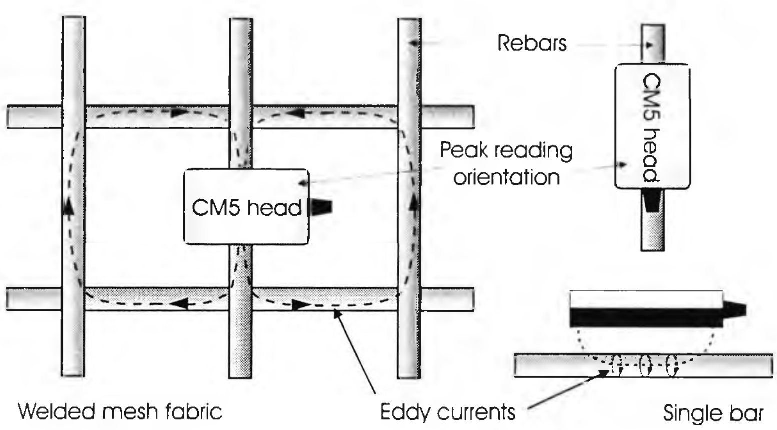


Figure 8.6 Eddy current effects on welded meshes and single bars

8.8.2. Cover Measurement of Reinforcement Bars

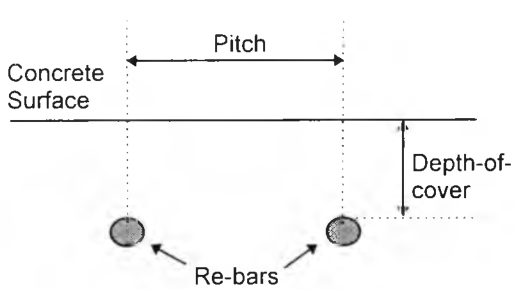
For accurate cover measurements, a few simple rules have to be complied. Firstly, cover should only be measured when the head is directly over the bar. Second, the long axis of the head should be parallel to the bar. Third, there should be no close neighboring bars to the bar being measured.

8.8.2.1. Effects of Neighboring Parallel Bars

In reinforced concrete, the main bars are usually placed in parallel and in the case of beams and columns, usually close to one another. The neighbouring bars will affect the covermeter reading and hence the ability of the covermeter to resolve the bar in question. The rule of thumb (Deichsel & Krell, 1987), if covers are to be just resolved for parallel bars, is that the centers between neighbouring bars (pitch) should exceed one and a half times the cover of bars. This can generally be applied to situations where the depth of cover is not too shallow, at which point the minimum pitch is determined more by the effective width of the head, and at very deep covers when the signal is too weak to display the dip in the traverse profile. At both these extremes, the pitch to cover ratio should be increased.

In determining the effects of pitch on cover measurement, the CM5 covermeter gave a -5% error at a pitch of 55mm for a cover of 50mm using 16mm high-tensile steel and of 1% cover error for pitches 75mm and above (Alldred, 1993). In a follow up experiment, pitch was kept constant at 75mm and the cover varied to determine the effects on measured cover. Here, an error of ≤ -5% was obtained for covers less than 65mm and ≤ -8% for deeper covers.

In general, if the pitch/depth ratio is less than unity, the bars will be neither resolved nor measured to acceptable accuracy. If the ratio is two or more, both clear resolution and high accuracy should be achieved with the CM5 covermeter (Figure 8.7).



$$\frac{Pitch}{Depth} < 1,$$ Unacceptable accuracy

$$\frac{Pitch}{Depth} > 2,$$ High accuracy

Figure 8.7 Effects of Pitch/Depth ratio on accuracy

8.8.2.2. Effects of Traverse Bars

In structural members, bars are not only set parallel but also in the perpendicular direction. These traverse bars form a mesh with the parallel bars and act either as structural reinforcing in two directions or as secondary reinforcement. The secondary bars can be of equal size to the main parallel bars, but are often smaller. The effect of traverse bars on cover measurement however is varied, depending on whether the search head is directional or non-directional. In the case of non-directional heads, a stronger signal will be received in the presence of traverse bars than its directional counterpart. This has the effect of producing a cover reading which is much shallower than is actually the case. Hence, directional covermeter search heads are less susceptible to traversing bars than it's non-directional counterpart. As the CM5 head is directional, reference from here on will only be made to this type.

To measure depth of cover in cases where the traverse bars are widely spaced, the search head should be placed parallel to the main bar and midway between the two traverse bars. In situations where the traverse bars are within the effective length of the search head, however, the search head should not only be placed over the main bar but also on one of the traverse bars so that the measurement is affected by only one traverse bar and not both, hence reducing any errors in measurement.

8.8.2.3. Effects of Multiple Bars

Some structural members use multiple bars of smaller diameter as an alternative to a single large bar to give a similar cross sectional area. Therefore, the use of n bars of diameter d is equal to a single bar of diameter $d\sqrt{n}$. For example, two bars would be the equivalent of a single bar of diameter, $D = d\sqrt{2} = 1.41d$ (CM5 CoverMaster User Manual), likewise three bars would give 1.73d and so forth.

8.9 Factors Affecting Re-bar Location & Cover Determination

Factors that could influence re-bar location and the determination of cover include:-

1. Age of construction - Reinforced concrete members have been used in the construction of structures since the early part of this century, although its use in multi-storey construction in Great Britain did not truly begin after the Second World War. Hence, the age of a structure may give an indication as

to the type and configuration of re-bars used. Fabric reinforcing was not widely used in structures until after 1960. It is therefore, reasonable to suggest that reinforcing which was not welded was used prior to this. It can also be noted, that twisted bars were faded out of use during this period.

2. Surface finish of the concrete - The surface finishes of reinforced concrete structures are predominantly flat. Depth-of-cover in these instances is exactly that read by the covermeter (plus or minus accuracy). In a small number of cases, however, there may be an exposed aggregate finish. This gives an uneven, indented finish to the member's surface. The depth of these indentations will affect the interpretation of cover to the re-bars.
3. Proximity of other structural members - If at the point of inspection, the slab is connected to another reinforcing member, the configuration of reinforcement would be different to that if the member was not present.
4. Location of inspection - Slabs may be inspected in one of two locations, either at a position close to or away from an edge. If slabs were to inspected away from an edge, then the most probable kind of re-bars located would be fabric reinforcing as the larger bars required to act against tensile forces would be below the neutral axis at this point. At the edges of slabs, usually supported on beams, a reversal of forces occurs requiring the larger bars to swap from a position below the neutral axis of the slab section to a position above it.
5. Diameter of re-bars - Known or unknown.
6. Type of re-bar configuration - Fabric or straight.
7. Type of steel - High yield or mild steel. These are generally used in the fabrication of re-bars.

Using this information, dependency between the use of fabric reinforcement, the age of construction and the location of the inspection can be made. There is also a relationship between the use of fabric reinforcement and the use of high yield steel in the fabrication of the reinforcing. These dependencies are illustrated in Figure 8.8.

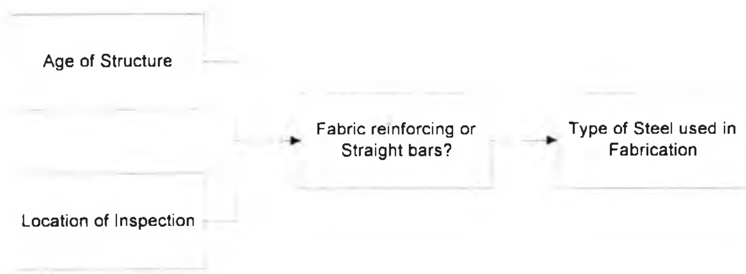


Figure 8.8 Dependencies between factors

8.10 Employing an Expert System

The factors discussed in the previous section determines the final strategy that would be used in determining re-bar size and depth-of-cover. To simplify the decision making process of operators in deciding which strategy to employ in a set of circumstances, the author recommends the use of an expert system that embodies the decision making process. Based on the interdependencies of the previous section, a 'knowledge diagram' can be constructed which represents the dependency between the factors above and the goal of choosing a strategy. This knowledge diagram is illustrates in Figure 8.9.

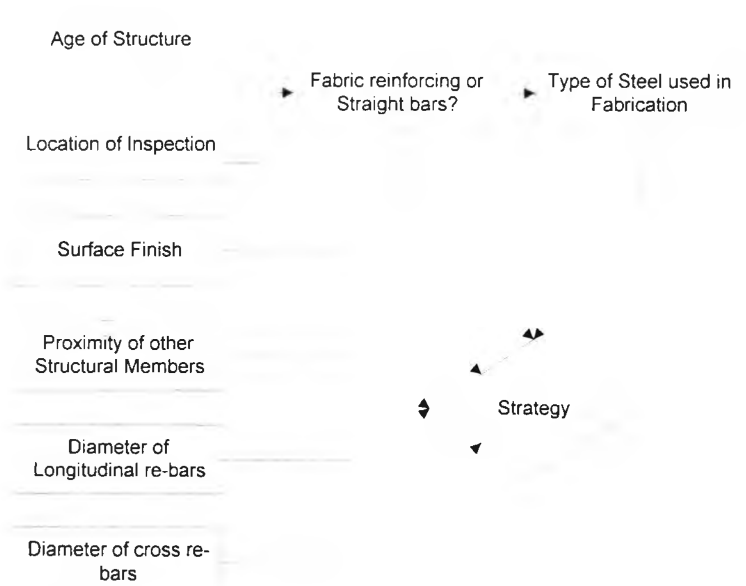


Figure 8.9 Knowledge Diagram on selecting a Strategy for Re-bar Detection & Cover Determination

8.10.1 Strategies

The author indicates that there are two main breeds of inspection strategies. Those for the location of re-bars whose diameter is known, and those for the location of re-bars whose diameter is not known. Within these breeds, there are should be a strategy for the location of re-bars in fabric reinforcement, and for non-welded reinforcing. This gives a total of four strategies. These strategies are shown in Table 8.1, taking the form of a simplified rule base.

Table 8.1 Factors affecting the choice of a Strategy

Inspection Strategy	Is diameter known?	Type of Re-bar
Strategy 1	Yes	Fabric
Strategy 2	Yes	Straight
Strategy 3	No	Fabric
Strategy 4	No	Straight

Of couse, as illustrated in Figure 8.9, there are many other factors that will affect the location, and cover determination of re-bars. For example, the type of steel used in the fabrication of the reinforcing, the surface finish of the slabs, and the location of inspection. The former two factors, however, do not affect the inspection strategy that is to be employed, but the variables used in the determination of depth-of-cover. As for the latter factor, the author feels that its effect was best taken care of during the implementation of the strategy.

8.10.2 Rules

Now that the dependencies and strategies have been determined, a final rule base may be constructed which represents all the dependencies (Table 8.2). It is beyond the scope of this thesis to develop this knowledge base system. However, the discussion of these few rules in context of a knowledge base system does demonstrate the potential of employing such a system within the covermeter inspection process.

Table 8.2 Rule table representing all dependencies

Strategy	Age of construction	Location of inspection slab	Type of steel	Components connected to slab	Type of re-bar	Closest re-bar diameter	Cross re-bar diameter	Surface finish on slab
Strategy 1	Post 1970	Middle	High yield	Beam or Column (B or C)	Fabric	Known	Known	Float (Fl) Form (Fo) Exposed aggregate (A)
Strategy 2	Any	Edge	High yield or Mild	B or C	Straight	Known	Known	Fl, Fo, A
Strategy 3	Post 1970	Middle	High yield	B or C	Fabric	Unknown	Unknown	Fl, Fo, A
Strategy 4	Any	Edge	High yield or Mild	B or C	Straight	Unknown	Unknown	Fl, Fo, A

8.11 Conclusion

There are a number of options possible in selecting a covermeter. In terms of technology, there are currently two common techniques. One measures the magnetic permeability of re-bars (magnetic reluctance technique), while another measures its electrical conductivity (eddy current technique). Covermeters that employ the eddy current technique are more stable to magnetic reluctance meters, as the latter are very susceptible to temperature changes, external magnetic fields and any magnetic aggregates in concrete.

Further to these two techniques, there are four kinds of covermeter head designs; U-core, Rod-core, Vertical coil and Air-cored. U-core head designs, even with its well-controlled distribution field are not common today, due to their instability. Rod-core head designs have the advantage of deep penetration but are susceptible to bar congestion. Vertical coil head designs are good at pinpointing the presence of re-bars but are not suited for welded meshes due to electrical conductivity. The air-cored head design is very much like U-cored heads with its well distributed field, but without its drawbacks.

In addition to these ranges, there are covermeters that have the ability to log data; and some, with the ability to log covermeter readings with displacement readings from a wheel based encoder, attached to the search probe head. With the latter, re-bar images are reproducible on an LCD output, or paper printout (see Figure 8.3). The latest covermeters have the capacity to estimate re-bar sizes automatically, a feature that has also been produced for the CM5 covermeter, in conjunction with a CROCUS robot (see Chapter 10).

The CM5 covermeter was employed in the research of this thesis for various reasons:

1. It complies with the accuracies set by BS1881:Part204:1988 (see Section 8.5).

2. It employs the more stable eddy current technique in re-bar detection.
3. It uses an Air-cored head design that produces a directional, well-controlled distribution field, but without the unstable drawbacks of the U-core head design. Furthermore, Rod-core head designs are unsuitable, as they are very susceptible to re-bar congestion, while Vertical coil heads are non-directional, and its performance degrades in the presence of welded meshes.
4. Finally, the CM5 CoverMaster covermeter was granted by Protovale (Gt. Britain) Ltd. for research purposes.

The CM5 covermeter has a depth of penetration, ranging from 30cm to 90cm with the standard search probe head. It produces a maximum voltage reading when its long axis is directly above, and aligned with a re-bar. This feature is used to determine both the location and orientation of a re-bar. In locating multiple (crossing) re-bars, an operator would start by making an informed guess of the reinforced structure. If the two layers are of a similar re-bar size, the closest layer would be determined first; alternatively, if of quite different sizes, the larger would be resolved first. Once this is determined, the operator would scan sideways, marking the maximum readings as encountered. Following this, the probe head would be rotated by 90°, and the operator would perform a scan between the previously located re-bars, and again marking the position of all peak readings. Finally, the first scan would be repeated, this time between the previously located re-bars to confirm the position markings of the first scan. The result should be an accurate location of all re-bars concerned.

As for depth-of-cover, to attain high accuracy in measurement, it is first necessary to know the size of the re-bar concern; and if this value is unknown, various methods are available for estimating it. These methods are discussed in the following chapter. It should be noted, however, that an estimate in re-bar diameter, an adjacent standard size larger or smaller; produce an error of less than 4%. Other factors that will also determine the accuracy of measurement are the close proximity of any neighbouring, and traversing re-bars, the absence of which improves accuracy. With respect to the former, the rule of thumb is that the pitches between re-bars should exceed $1^1/_2$ times the depth-of-cover, for re-bars to be resolved and for cover determination to be accurate. The effects of neighbouring and traverse re-bars on depth of cover determination are discussed further in Chapter 10.

The chapter also demonstrated the potential of employing a knowledge based system to the covermeter inspection process by discussing the various factors that would affect the process. These factors include the age of construction, surface finish, proximity of other structural members, location of inspection, diameter of re-bars, type of re-bar configuration and type of steel used.

9. Cover and Re-bar Size Estimation Methodologies

9.1 Introduction

To determine the depth of cover of a re-bar using a covermeter, the size of the re-bar has to be known in advance for accurate determination. Sometimes, this is provided in site drawings, but most often this is not available and therefore a means of determining the bar size is very useful. The damaging method of drilling to determine a bar size is not commonly used today. This is only used where the bar diameter accuracy is crucial to the work at hand. It should be noted, however, that a change in bar diameter to an adjacent size produces an error in indicated cover of less than 4% (CM5 CoverMaster User Manual). Therefore, an approximate knowledge of bar diameter is sufficient to determine cover to an acceptable accuracy.

Where bar size estimation is required, at least one additional measurement will be necessary in order to determine the two unknowns, cover and re-bar diameter. There are currently four different methods of re-bar size estimation, this chapter covers each of them in turn. A new method is introduced, with in-depth coverage provided in the following chapter. The methods described here were attained from empirical experiments. Each method will be described in respect to the CM5 covermeter, though they can be applied to other covermeters.

9.2 The Five Estimation Methodologies

9.2.1 Spacer Method (Manual and Automated)

The spacer method is manual in operation and applies the technique proposed by the BS1881.204 British Standard. This method can be used successfully with the CM5 covermeter and, with care, can yield accurate results. A non-metallic spacer of thickness t is required for this test.

To begin the test, the gain of the covermeter is put to its maximum setting by selecting the minimum diameter setting on the CM5 covermeter. If the test re-bar is known to be larger than this minimum diameter setting, a larger diameter setting can be selected appropriately. The covermeter is then zeroed by taking readings in air, away from any magnetic media. The orientation of the re-bar is then measured using the technique mentioned in Section 8.8.1, i.e. by rotating the head over the re-bar to obtain a peak reading. When this is done, cover measurements can be made by placing the head with its long axis parallel to the orientation of the re-bar. Next, another cover reading is obtained, but this time with the spacer of thickness t inserted between the head and the surface of the concrete. This procedure is carried out with the next diameter setting on the covermeter, one size up to the previous until all settings are obtained.

The next stage is to subtract the spaced cover reading from the standard (direct) cover reading for each diameter setting, and then to compare these results to the spacing thickness t. The one which produces the closest result to the value t is the one with the appropriate diameter setting, which is the variable to be determined. With covers of less than 30mm, the head has to be turned over and the white surface used instead. If this is done, 30mm have to be subtracted from each cover reading. For convenience, the white surface can be used in place of the afore mentioned spacer. However, this is only possible for covers greater than 30mm and less than 60mm as the range of the standard head is from 30 to 90mm.

The limitation of the spacer method is that it relies on comparing small changes in differences between readings and is therefore influenced by any errors in measurement. Secondly, this method depends strongly on obtaining very different cover readings with varying bar sizes but as mentioned, this variation is small. Therefore, in many instances, the differences between covers with and without a spacer amounts to two very close differences for two adjacent diameter settings. This method can be improved by the use of two or more spacers of varying thickness, but the improvement is at the cost of convenience and time. Some modern covermeters in-build this functionality, making the process more automatic. However, the process still inherits the method's limitations. The limitations of this method is further reviewed by Shirley (1971) and Wheen (1974).

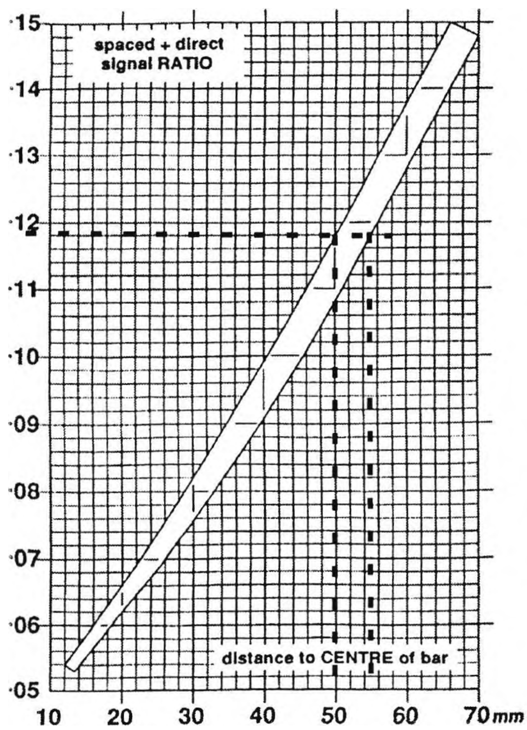
Considering the procedure of performing the estimation, this method can easily be automated with a robot.

9.2.2 Spacer Ratio Method (Manual and Automated)

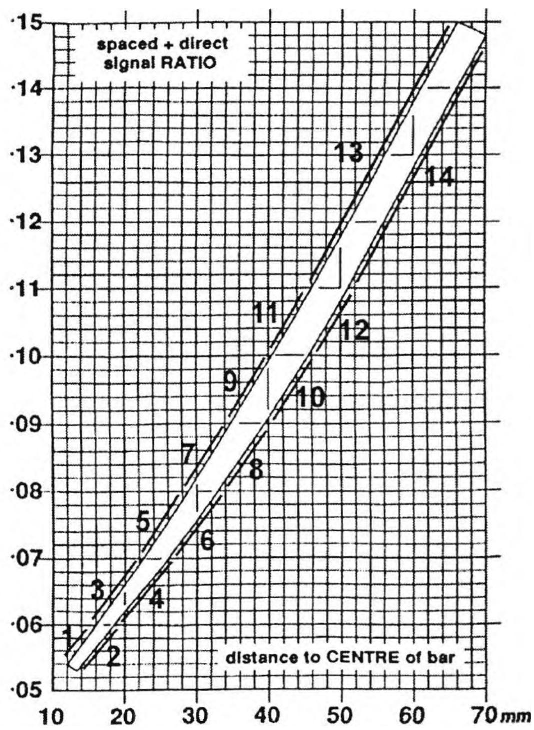
The second method is manual in operation and is actually an improvement to the previous method. Instead of using the differences in cover, as in the spacer method, the ratio of the two readings is used to determine the size of the re-bar (Alldred, 1993). This method is the proposed method in the CM5 covermeter manual for re-bar size determination over the more conventional "spacer method". A means of computerising this method with a robot has been determined, but before discussing this, the next few paragraphs will first describe the spacer ratio method.

The method is divided into two stages. In the first stage, the CM5 covermeter is selected to indicate signal strength. This setting measures the eddy current produced in the presence of a magnetic medium, like a re-bar. Next the covermeter is zeroed in air. With the long axis of the head parallel to the orientation of the re-bar and directly above it, a reading is obtained with the white surface of the head and then the black. To improve accuracy in the results obtained, use a bar diameter setting larger than that anticipated if the cover is less than 35mm and conversely set the diameter setting to a smaller one if the expected depth of cover is greater than 35mm. Furthermore, the spaced reading should be greater than 0.03V and the standard reading not more than 1.9V.

Next, divide the spaced value by the standard value to obtain a value between 0.050 and 0.190, and then refer to the graph depicted in Figure 9.1(a) to obtain a range of depth (Alldred, 1993). The graph has a pre-plotted band of white/ black ratios vs. distance to centre of bar. This band encloses 80% of all experimental points. The range obtained from the graph covers therefore the most probable distances (including the likely error) from the surface of the concrete to the centre of the bar. To obtain the depth of cover, it is necessary to subtract the radius of the bar from the distance to the centre of the re-bar and the next stage covers this. The first stage is illustrated at the top of Table 9.1.



(a) Original graph



(b) Proposed method of automation

Figure 9.1 The graph used to convert space/ direct signal ratio to the distance to the centre of the re-bar

The second stage is carried out to determine both re-bar radius and depth of cover. A worksheet like the one shown in Table 9.1 (cursive print shows user input) is provided for this stage. For each diameter setting, the cover reading is obtained and to this the appropriate radius is added, the result is placed in the last column. When measurements for all the diameter settings are completed, the last column is inspected to find any value which falls between the lower and upper limits for the distance to centre previously noted. The figures provided in the Table 9.1 is a test sample provided by the User Manual and is given here to demonstrate it's usage. Looking at the test sample, the final results indicate that the diameter of the bar under test is 16mm with indicated cover of 45mm and distance to centre of 53mm. These results compare well with the actual test measurements of 16mm at 44mm cover.

In the small instances where the results obtained correspond to two values that fall within the same distance to centre band, the most probable answer will be the smaller of the two sizes and the average of the two covers. In all cases, the accuracy is to ±1 standard bar size and a cover measurement accurate to ±2mm or ±5%, this being within the standard laid out in BS1881:Part204.

Table 9.1 A similar worksheet to this is provided by Protovale Ltd. to be used with it's CM5 covermeter, this one showing example results

Stage 1

	WHITE		BLACK		RATIO
Signal:	.085	÷	.720	=	.118

	MINimum		MAXimum
GRAPH	50	to	55

compare

Stage 2

Cover:

DIAM	COVER	+	RADIUS	=	Distance
Ø 5		+	2.5	=	mm
6	34	+	3	=	37
7	36	+	3.5	=	39.5
8	38	+	4	=	42
10	40	+	5	=	45
12	42	+	6	=	48
16	45	+	8	=	53 ✓
20	47	+	10	=	57
25	49	+	12.5	=	61.5
32		+	16	=	
40		+	20	=	

The difficulty in automating the spacer ratio method lay in the computerisation of the graph in Figure 9.1(a). The author however, found a means of accomplishing this, and it is depicted in Figure 9.1(b). To computerise the graph, the author proposes using 14 straight line equations that fit the curves in the graph. These equations relate to 7 ranges in the space/ direct signal ratio and make up the whole range of the original graph. Once this was computerised, the whole procedure of automating the method on a robot is straight forward.

With the ability to computerise the graph in Figure 9.1, this method can easily be automated with a robot.

9.2.3 Orthogonal Method (Manual Only)

This method was first introduced by Tam in 1977 and is also based on solving two unknowns, cover and re-bar size, by measuring the same bar under two sets of condition. In the previous two methods, a non-magnetic spacer was used to obtain these two sets of conditions. One measurement was taken directly and the other with the spacer to give a different depth of cover, hence providing the second condition. In this method however, the second condition is achieved by taking the second measurement with the head at 90 degrees to the first measurement, i.e. the long axis of the head being perpendicular to the bar under test. And thus, the method is known as the Orthogonal method.

Before this method can be applied to site testing, calibration charts for both parallel and perpendicular readings have to be drawn for the specific covermeter. For this, parallel signal readings are obtained for covers typically ranging from 10mm up to 100mm (30mm-90mm for the CM5 covermeter) for bar sizes ranging from 5mm up to 40mm. These results are then plotted on a signal strength versus cover graph to obtain a family of curves each representing bar size. Likewise, a similar chart is obtained for perpendicular readings to give a second chart of signal strength versus cover. These two charts are then ready to be used to predict cover and bar size by using an iterative method of deduction. A similar table to that shown in Table 9.2 is used by Tam (Das Gupta & Tam, 1983) to aid in the iterative process.

Table 9.2 An iterative table used in the Orthogonal method (* represent a range of values obtained from charts)

	Range of Cover (mm)		Range of Diameter (mm)	
Step	Parallel	Perpendicular	Parallel	Perpendicular
1	*		*	
2		*		*
3	*		*	
4		*		*
5	*		*	
6		*		
•		•	•	
•		•	•	
•		•	•	
•		•	•	*
	Final Cover		Final Diameter	

The iterative table (Table 9.2) demonstrates the steps taken in coming to a final set of diameter and cover values. The table works on the process of iterative elimination of cover and re-bar size estimation. In the first step, a parallel signal reading is obtained and this value is then looked up in the parallel chart. This single value will give a range of covers and diameters which is then placed in the first column of the table. In the second step, the value from the first column is then copied into the second column, depicted by the broken arrow as the cover range will still fall in this band. This cover band is then looked up in the perpendicular chart to give a range of possible diameters which is then placed into the second column and then also copied into the third column. The range of diameters is then used to obtain a range of covers from the parallel chart and the whole process is repeated till finally a single value of diameter and cover is obtained as each iterative process produces a smaller range of values. The accuracy of this technique has been claimed to be accurate to ±1 standard bar size and ±5mm depth of cover. The accuracy does fall within the BS1881:Part204 standard, but the technique doesn't lend itself to ease of use as reading of the charts is cumbersome and time consuming, especially with the iterative nature of the process.

This method is too complex and too slow, even when automated with a robot to make it practical. The graphs used in this method are also far more complex than that of Figure 9.1, computerization of which might be near impossible. The author therefore, does not recommend this method for automation.

9.2.4 Orthogonal Ratio Method (Manual and Automated)

Like the previous method, this method also uses a parallel and a perpendicular reading but this time the ratios of the two is taken to determine the bar size and cover. This method was recently introduced in 1995 by J. Alldred, and follows on the spacer ratio method explained earlier in Section 9.2.2.

To use this method, a chart has to be drawn up with the ratios of perpendicular signal reading to parallel readings versus cover for the covermeter to be used. From experiments carried out by J. Alldred on the CM5 and CM9 covermeters, a band of perpendicular/ parallel ratios was found for each bar diameter irrespective of cover. Thus, the size of a re-bar can be determined by taking the ratio of it's perpendicular reading to it's parallel reading to obtain a ratio no greater than 1. This value can then be referred to on the chart to determine the size of the re-bar. To simplify matters further, a lookup table like the one shown in Table 9.3 can be drawn up for on site use. This tabulated result is specific only to the CM5 covermeter (Alldred, 1995). And once the diameter of a re-bar has been determined, the covermeter can be used in the conventional way to resolve for depth of cover.

Table 9.3 Lookup table for the Orthogonal ratio method to determine bar size from the ratio of perpendicular to parallel signal readings for the CM5 covermeter

Ratio	Diameter	Ratio	Diameter
<		.180	
	5		20
.035		.198	
	6		22
.050		.215	
	7		25
.066		.260	
	8		28
.078		.340	
	10		32
.102		.415	
	12		40
.135		.500	
	14		50
.160		>	
	16		
.180			

The results in Table 9.3 were obtained from measurements on a single bar. In practice however, it is very uncommon to find bars in isolation. Therefore, it is important to find out at which point the results in Table 9.3 will be deemed unusable under practical conditions. From experiments (Alldred, 1995) on the effects of bar congestion on the results obtained using Table 9.3, it is found that the effect of neighbouring parallel bars on parallel readings is not as much as that for the perpendicular readings. In fact, perpendicular readings were affected beyond the 10%

tolerance error in signal measurement obtained when a neighbouring bar was almost half the distance as was for the parallel readings. Therefore, it is the perpendicular reading which sets the tolerance limit on the distance between parallel bars, this being 103mm for a single neighbouring bar and about 115mm for neighbouring bars on either side. The results obtained above were for 16mm re-bars at 30mm depth of cover. Similarly, experiments were done on the effects of 10mm traverse bars on a 25mm bar with a depth of cover of 35mm. The experimental result indicated that the tolerable traverse distance is 80mm. It can therefore be assumed that acceptable results will be obtained providing the distance between bar centers exceed a minimum limit of about 100 to 150mm. This, however, is dependent somewhat on head dimensions, and also on concrete cover.

As regards to the suitability of this method to automation, it can easily be seen that this method lends itself to it. In fact, the CM9 covermeter does exploit this process. It has all the necessary software and in-built microprocessor to automate the process. However, with regard to the automation of this process, the implementation is protected by a Patent granted to Protovale (Oxford) Ltd.

9.2.5 The Traverse Profile Width Method (Automated with CURIO)

The Traverse Profile Width Method uses the width of the response of the CM5 covermeter as the search probe is scanned across a bar to determine it's depth from the surface of concrete to the center of the bar. This method is described in detail in the next chapter. This method was investigated as the ability to traverse scan a surface to determine all three unknowns; locations of re-bars, their sizes and depth-of-cover were very promising. Unlike, the previous four methods that require spot readings, the Traverse Profile Width Method is based on a traverse scan and is therefore much quicker in determining the three unknowns.

Previous investigations by other researchers in the field tried to tie the variation of traverse profile width to bar diameter or depth of cover only to find that the results were insufficiently distinct to allow a meaningful interpretation. In this latest traverse method however, a relationship is found to relate the traverse width to the distance from the surface of the concrete to the center of the bar, but independent of bar diameter. As a result, by using the covermeter initially to indicate signal strength, the distance to the bar's center can be determined directly without the need for prior knowledge of bar size. By next using the instrument as a conventional covermeter, the bar diameter can be deduced as being that value at which the indicated cover plus half the diameter equals the previously-determined distance to center.

This technique can be applied using any covermeter that is capable of indicating signal strength. Though this method can be applied manually using a graph to convert traverse width to distance to center, or by using a specially-prepared ruler scale to measure the width; it lends itself better to instruments that are able to log traverse distance with the signal readings. Examples of these include the covermeters reported earlier, the Ferroscan FS10 and the Profometer 4, both use a wheel based encoder to measure traverse distances. However, these instruments do not provide accurate traverse measurements as they depend on a human operator in the scanning process. For example, the slipping of wheel encoders is not uncommon, especially on uneven surfaces. Keeping the traverse scan on a dead straight line is another difficulty. The latter can be aided with a ruler but this could prove cumbersome for on site use, especially when the operator is on a harness a 100m up a building.

This is where robots can dramatically improve on the accuracy of measurement and if sufficient computing bandwidth is available to allow real-time analysis of the covermeter signals, the whole process can be automated. To investigate this process, a CM5 covermeter was automated with an industrial cartesian gantry robot, CROCUS. The automation is intended for CURIO, an in-house robot being developed at the Unit for inspection purposes, but this was not ready for use at the time. The process was only recently ported onto CURIO, when it first became available in April 1995. As the coverage of CURIO/ CROCUS robot and how it relates to the CM5 covermeter is important to describing the experiments needed for the affirmation of the traverse method, it is described next, before the in-depth coverage of the traverse method.

9.3 Conclusion

All five methods discussed in this chapter meet the accuracies set by the BS1881:Part204 standard, i.e., estimation to ±1 standard bar size, and cover measurements accurate to ±2mm or ±5%. The spacer method, however, has to be used with great care to obtain this accuracy, as the method relies on comparing small changes in differences between readings, and are, therefore, prone to errors. With the exception of to the Orthogonal Method, the methods discussed in this chapter can be automated quite easily with a robot. The Orthogonal Ratio Method, however, is protected by a pending patent, and therefore, cannot be used in this project. Leaving out the spacer method due to its susceptibility to errors, this leaves the Spacer Ratio Method, and the Traverse Profile Width Method for the automation process.

The latter is based on performing a traverse scan in determining the location, size, and depth-of-cover of re-bars, while the former is based on spot readings. The author, therefore, recommends the Traverse Profile Width Method for this project, as it is much faster than the latter method. The latter method, however, can be employed in reaffirming re-bar size estimations.

The following chapter discusses the Traverse Profile Width Method.

10. Theory and Experimental Verification of the Traverse Profile Methods

10.1 Introduction

This chapter develops the theory involved in fitting a function to a traverse profile of a covermeter scan across a reinforcing bar. This is necessary as a first stage to the automation of covermeters for robotic usage. Since there are two unknowns to determine from a covermeter traverse profile scan, depth-of-cover and re-bar diameter; another function is needed for their evaluation. This second function is determined from experiments, and is found to be related to various properties of the traverse profile. This chapter discusses these required profile properties and the experiments undertaken to support this Traverse Profile method. Practical properties, like the effects of neighboring re-bars on the effectiveness of the theory, are also covered. The experimental equipment used in performing all the experiments in this chapter is discussed in Appendix E, with full experimental results summarized in Appendix F.

10.2 Traverse Profile Theory

When a covermeter search probe is traversed sideways across the line of a single reinforcing bar, and the signal strength is plotted as a function of off-center displacement; a symmetrical bell-shaped traverse profile is obtained which has a single peak at zero displacement. A plot of such measurements is shown in Figure 10.1, together with two possible theoretical curves. The first theoretical curve is a Gaussian function of the form $y = A + B\ exp(-x^2/s^2)$ (Carino, 1993). This function provides a reasonable fit to a typical covermeter traverse profile, shown as the lower dashed curve on the plot of Figure 10.1. The Gaussian plot, however, is not based on any theoretical or physical justification, but on the approximate fit of the curve to typical covermeter signal readings.

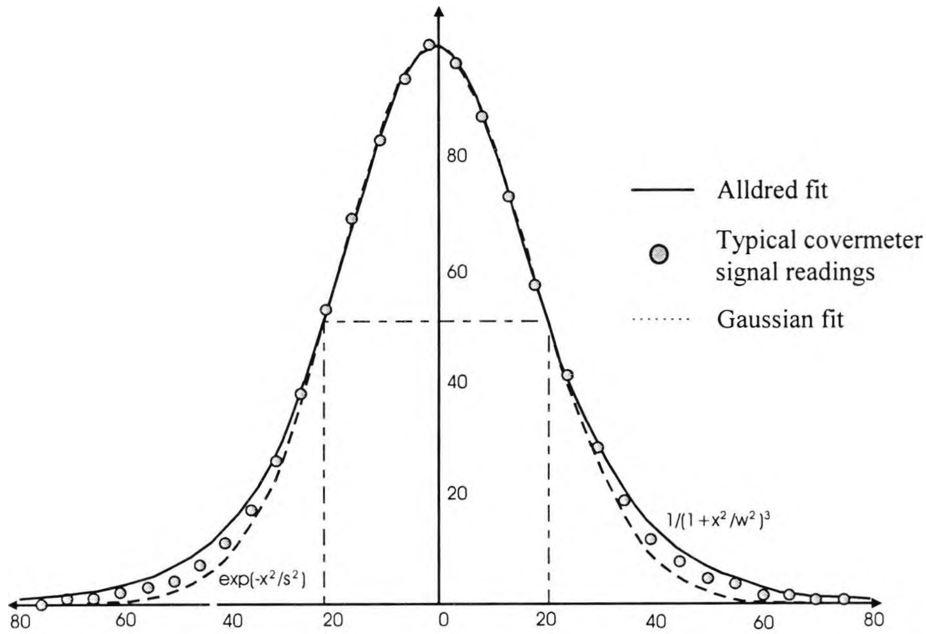
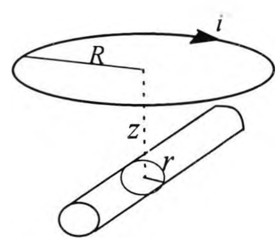


Figure 10.1. Traverse profile across a single bar.

The second theoretical fit, shown solid in Figure 10.1, is derived from first principles (Alldred, Chua & Chamberlain, 1995). For a small circular target of radius *r* at a distance *z* from a circular coil of radius *R* and on its axis, the magnitude of the coil voltage *v* induced as a result of eddy currents induced in the target by the cessation of a current pulse *i* in the search coil can be derived from first principles and is given in Equation 10.1, where *t(r)* is the decay time-constant of the conducting target and *K* is a dimensionless constant determined by the units of measurement.



$$v = K\,L\,i\,R^3\,r^3\,t(r) / (R^2 + z^2)^3$$

Equation 10.1

When using commercially-available instruments, the quantities *L* and *i* are not usually under the control of the user; and in most cases, the value *t(r)* cannot be derived from first principles. It is therefore more convenient to simplify all the terms in the numerator into a single function of *A(r)*, so that the expression reduces to Equation 10.2.

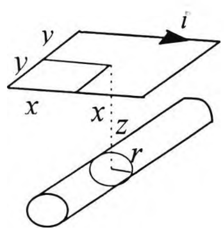
$$v = A(r) / (R^2 + z^2)^3$$

Equation 10.2

This equation can readily be solved for z, as shown in Equation 10.3.

$$z = (\sqrt[3]{[A(r)/v]} - R^2)^{1/2} \qquad \text{Equation 10.3}$$

Expressions for the signal received by coils of non-circular shape, particularly polygons with a small number of sides, can also be derived, especially if a simplified numerator is acceptable; for example, a rectangular coil of side lengths *x* and *y* yields Equation 10.4.



$$v = \frac{A(r)}{\left(\left(\frac{x}{2}\right)^2 + z^2\right)\left(\left(\frac{y}{2}\right)^2 + z^2\right)\left(\left(\frac{x}{2}\right)^2 + \left(\frac{y}{2}\right)^2 + z^2\right)}$$

Equation 10.4

Equation 10.4 is clearly more complex than Equation 10.2; however, for any given value of *z* it is possible to solve for an effective value of *R* which yields the same value of *v*. For example, in the special case of a square coil with $x = y$: when $z^2/x^2 = 0$, the required value of R^2/x^2 is $\sqrt[3]{2} = 1.2599$; and as z^2/x^2 tends to infinity, R^2/x^2 tends to $4/3 = 1.333$. These results were obtained by equating Equation 10.2 to Equation 10.4 (see Appendix D). In practice, the 6% increase in R^2 with increasing z^2 is not very significant, especially when it is realized that for very large *z*, a straightforward inverse sixth power law would have adequately represented the variation of *v* with *z*, i.e. *R* could alternatively reduce to zero. The concept of an "equivalent radius" can be tested by taking measurements of *v* for varying *z*, and plotting $1/\sqrt[3]{v}$ versus z^2. It will be found that a straight line is obtained which intercepts the negative z^2 axis at approximately $1.26x^2$.

In the case of a covermeter such as the Protovale CM5 CoverMaster, the search head contains two square coils wired in anti-phase, the circular eddy current path is below their common edge, and the plane of the current path is perpendicular to the plane of the coils. An expression for the signal voltage can be derived but this is rather laborious, as it is considerably more complicated than Equation 10.4. Nevertheless, by plotting experimental measurements of $1/\sqrt[3]{v}$ versus z^2 for a reinforcing bar, and treating R^2 as a parameter to be determined by experiment, rather than an actual physical quantity, it was found that the simple Equation 10.2 still gave a straight line (Experiment 1 in Appendix F-1 gives correlation coefficient values of r^2 = 0.998), providing that the value of z plotted is the distance from the plane of the coils to the center of the bar and not depth-of-cover. Thus the z^2 term is replaced by $(c+r)^2$, where c is cover. If this is repeated for a variety of bar sizes, a family of lines is obtained, with different slopes equal to the empirical scaling factors $1/\sqrt[3]{A(r)}$, but the same negative z^2 axis intercept.

Table 10.1, list a few average values from the many experiments performed on 8mm, 10mm, 12mm, 16mm and 20mm re-bars. A fuller experimental result listing is provided in Appendix F-2. Note that the slope values for each bar size in Table 10.1, are distinct and that the coil dimension are near enough constant for all sizes. Repeatability of results are shown for both the 10mm and 20mm re-bar sizes, represented by (I) & (II) respectively. Using the values in Table 10.1, concrete cover can be calculated from signal strength by using Equation 10.3, and subtraction of the bar radius.

Table 10.1 Experimental results of $1/\sqrt[3]{A(r)}$ and R^2 for different re-bar sizes with two experimental results for the 10mm and 20mm re-bars respectively

Bar size	Slope ($1/\sqrt[3]{A(r)}$)	Intercept	R^2 (Coil Dimension)
8mm	4.77e-04	4.60e-01	964
10mm (I)	4.59e-04	4.47e-01	973
10mm (II)	4.52e-04	4.26e-01	943
12mm	4.10e-04	4.07e-01	994
16mm	3.51e-04	3.44e-01	980
20mm (I)	3.15e-04	3.26e-01	1030
20mm (II)	3.11e-04	3.02e-01	970

In principle, it is possible to derive the signal strength from a bar whose lateral position is not under the center of the coil; however the expression becomes even more complicated, and therefore unlikely to be useful. The preference is to find a simpler empirical relationship which is an adequate approximation. One would incline to hypothesize that an expression for the off-axis response might be obtained by adding in the square of the side-way position as in Equation 10.2 for the coil radius to arrive at Equation 10.5.

$v_x = A(r)/(R^2 + z^2 + x^2)^3$ Equation 10.5

As the predominant concern is with the variation of signal with lateral displacement, x; it will suffice to express the off-axis signal v_x in terms of the on-axis signal v_0 (see Figure 10.2) as in Equation 10.6, where the width term $w^2 = R^2 + z^2$.

$v_x = v_0 / (1 + x^2/w^2)^3$ Equation 10.6

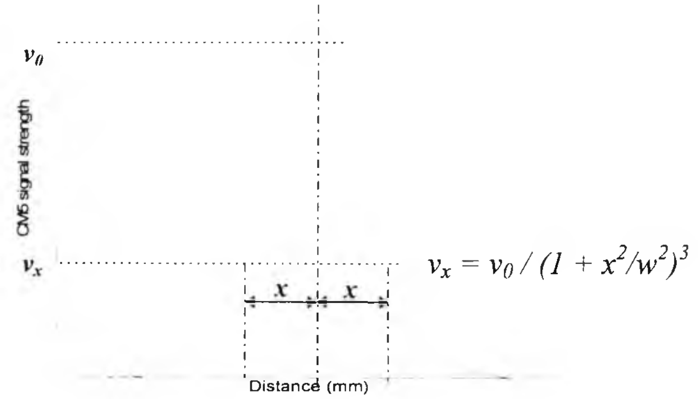


Figure 10.2 A traverse profile showing an off-axis signal reading v_x

Equation 10.6 is shown in Figure 10.1 as the upper continuous curve. This can be compared with the Gaussian function used by Carino (1993) shown as the lower dashed curve in Figure 10.1. From Figure 10.1, it can be seen that the two functions are indistinguishable for $v_x / v_0 \geq 0.5$, but noticeably different at larger values of x. The measured points fit either curve for $v_x / v_0 \geq 0.5$, but lie between the two functions for greater values of x.

Both the Gaussian function and Equation 10.6 provide a good approximate to a traverse profile for values of v_x / v_0 in the region of 0.5 or greater but is inaccurate for values of v_x / v_0 in the region of 0 to 0.5. Therefore, instead of taking the result from either equations (Gaussian or Equation 10.6), the author proposes taking the average result of the two. By doing so, a more accurate fit will be obtained for any measured traverse profile.

10.3 Traverse Profile Width Method

The Traverse Profile Width method uses a single width parameter to define a traverse profile, the full width of the curve at half height, $W_{1/2}$ (Figure 10.3). This is nearly, but not exactly, equal to the parameter w in Equation 10.6. When $x/w = 0.5$, $v_x \ / \ v_0 \ = 1/(1.25)^3 = 0.512$; and when $v_x / v_0 = 0.5$, $x/w = 0.510$ and $w/x = 1.961$.

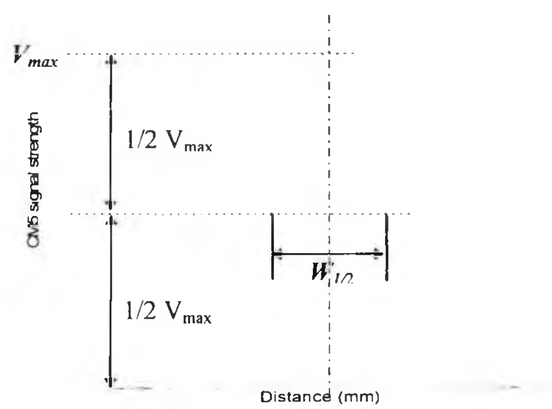


Figure 10.3 A traverse profile showing a traverse profile width at half-height ($W_{1/2}$)

Previous published work by Carino (1993) has tended to conclude that variation of traverse width with concrete cover is not adequately consistent, and that the variation of width with re-bar diameter is not adequately conclusive to be able to make meaningful analysis of these curves. This is demonstrated in the following plot of traverse profile Width vs. Cover for five re-bar sizes and a variety of covers (between 20mm and 60mm) using a CM5 covermeter is shown in Figure 10.4. A fuller experimental result listing is provided in Appendix F-2. Although the points from each re-bar size show a consistent trend, the five re-bar sizes yield different widths for the same cover, and so this plot cannot be used to convert traverse width to cover for a re-bar of unknown size on its own.

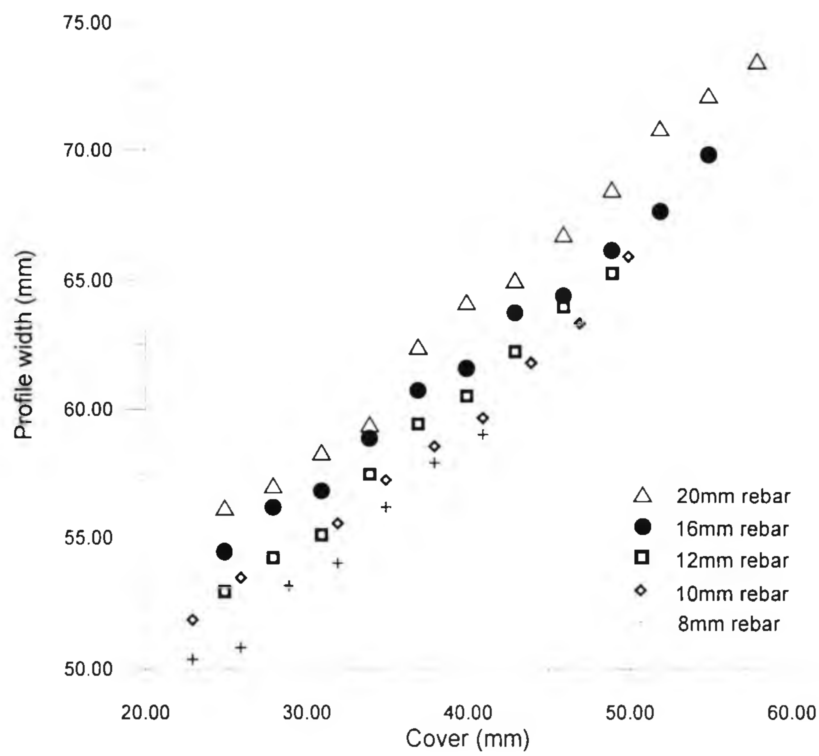


Figure 10.4 A plot of Profile width versus Cover using a CM5 covermeter

However, from further analysis, a simplified theory predicts that the traverse profile width should be a simple function of search-head width and the distance from the plane of the search-head windings to the center of the re-bar, and independent of re-bar diameter. This theory is verified by the results plotted in Figure 10.5. This plot is similar to Figure 10.4, but instead of plotting traverse width versus cover, it plots traverse width versus cover plus re-bar radius. In this latest plot, the results of all five re-bar sizes fit the same line Y = 0.548X + 35.654 with a correlation coefficient r^2 = 0.984. Y in this case is traverse width and X is distance to center of re-bar. Rewriting this in the conventions used here, the above equation becomes $W_{1/2} = 0.548z + 35.654$. This equation can therefore be used to convert traverse width to distance-to-center for any re-bar diameter.

Figure 10.5 includes two lines of ± 2mm from the best fit line as a visual indication to the accuracy of the fit. A repeat of this experiment produced another straight line fit of $W_{1/2} = 0.557z + 35.199$, with a correlation coefficient $r^2 = 0.988$. The values used hence forth is an average of the two experiments; $W_{1/2} = 0.556z + 35.205$. This equation can be rewritten to solve for z as follows:

$$z = 1.799\, W_{1/2} - 63.318 \qquad \text{Equation 10.7}$$

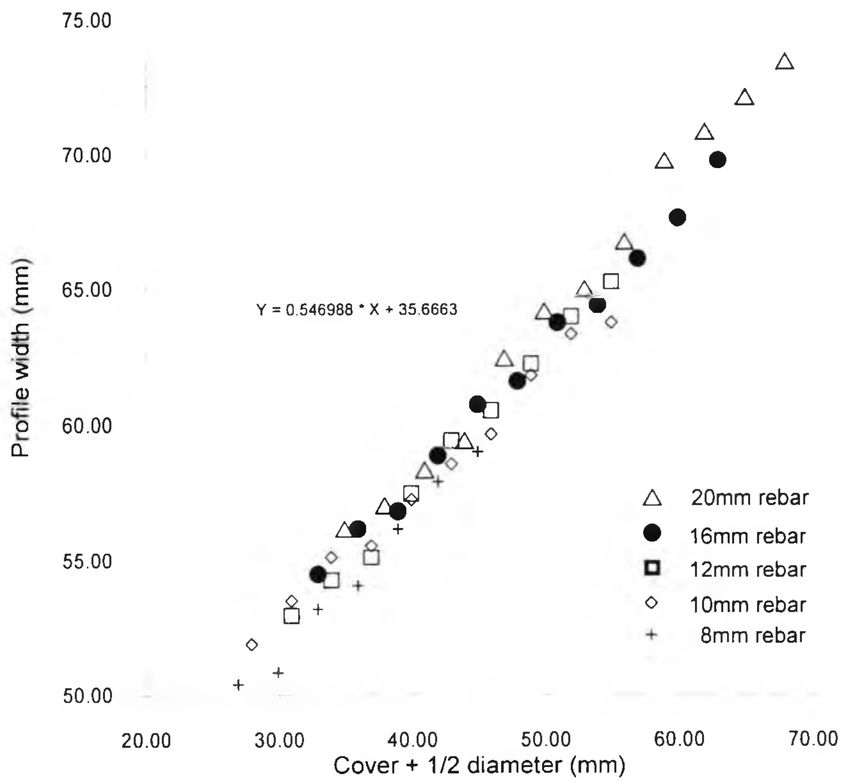


Figure 10.5 A plot of Profile width versus Distance-to-Center using a CM5 covermeter

If the re-bar diameter is known, cover can be determined from the knowledge of z by subtracting the re-bar radius from the value of z. However, if the re-bar diameter is unknown, it is still possible to determine cover as the value of the peak signal leads to a list of possible pairs of values of diameter and cover, of which the true result should be the pair, where the cover plus half-diameter equals the distance-to-center obtained from the traverse profile width.

By using equations, $z = (\sqrt[3]{[A(r) / v]} - R^2)^{1/2}$ (Equation 10.3), $z = 1.799\ W_{1/2} - 63.318$ (Equation 10.7), and values of $1/\sqrt[3]{A(r)}$ and R^2 from Table 10.1, the whole process of re-bar size determination and cover measurement can be automated for the CM5 covermeter. Before the process can be fully automated however, it first has to be able to extract the traverse profile width at half height and the maximum signal reading. There are various methods of achieving the automatic extraction of the traverse profile width, of which the gradient method has been used. The gradient method involves searching in a direction parallel to a single variable until the maximum or minimum value for the function is found for that variable. The process is then continued for the remaining variables until the local maximum or minimum is found. And to make the whole process practicable in the real world, the effects of neighboring re-bars (traverse and parallel) are investigated in the next two sections.

10.4 Effects of Traverse Re-bars

If one or more re-bars, traverse to the re-bar being measured, are present within the detection range of the search probe, they can be expected to contribute to the received signal. However, if the distance of the search probe to the traverse re-bars remain constant during the scanning process, the contribution to the signal component received will also remain constant, and will in practice merely result in a zero baseline shift as in Figure 10.6. Therefore, in the presence of traverse re-bars, the value of $W_{1/2}$ should not be taken as the width at half the peak height but as the width at an amplitude midway between the maximum and minimum signal strengths, i.e. using $V_{meas} = 1/2\ (V_{max} + V_{min})$ instead of 1/2 V_{max}.

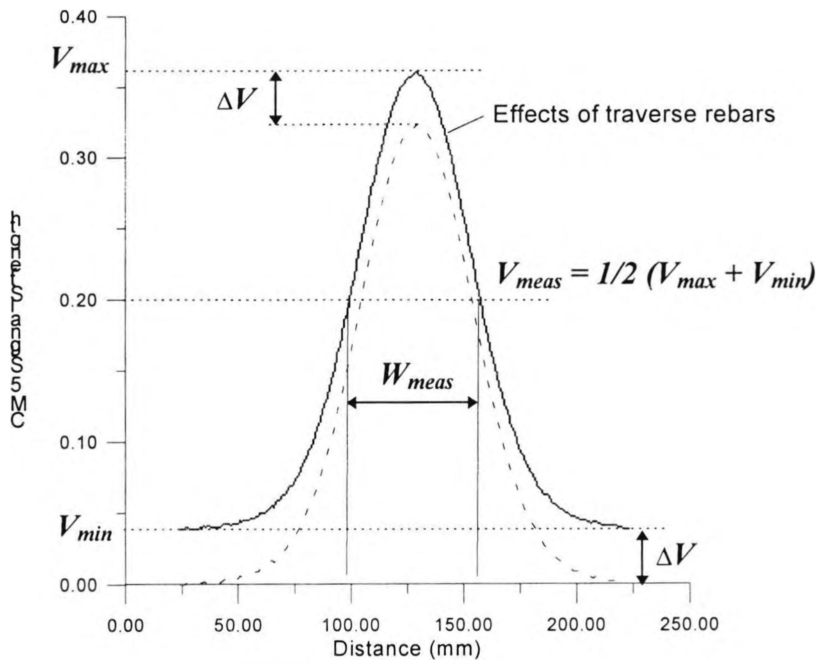


Figure 10.6 Effects of a traverse re-bar on a traverse profile scan

10.5 Effects of Parallel Re-bars

The presence of parallel re-bars on either side of a re-bar that is being scanned for its traverse profile has an overall effect of increasing the signal readings measured in the region of the central re-bar. The increment in the measured signal is the summation of the signals from each of the contributing re-bars to the one being measured, and the effect is shown in Figure 10.7. Figure 10.7 shows a traverse profile for a 20mm re-bar with a cover of 35mm and pitch of 100mm. The dashed plot in the figure is for a single 20mm re-bar at 35mm cover.

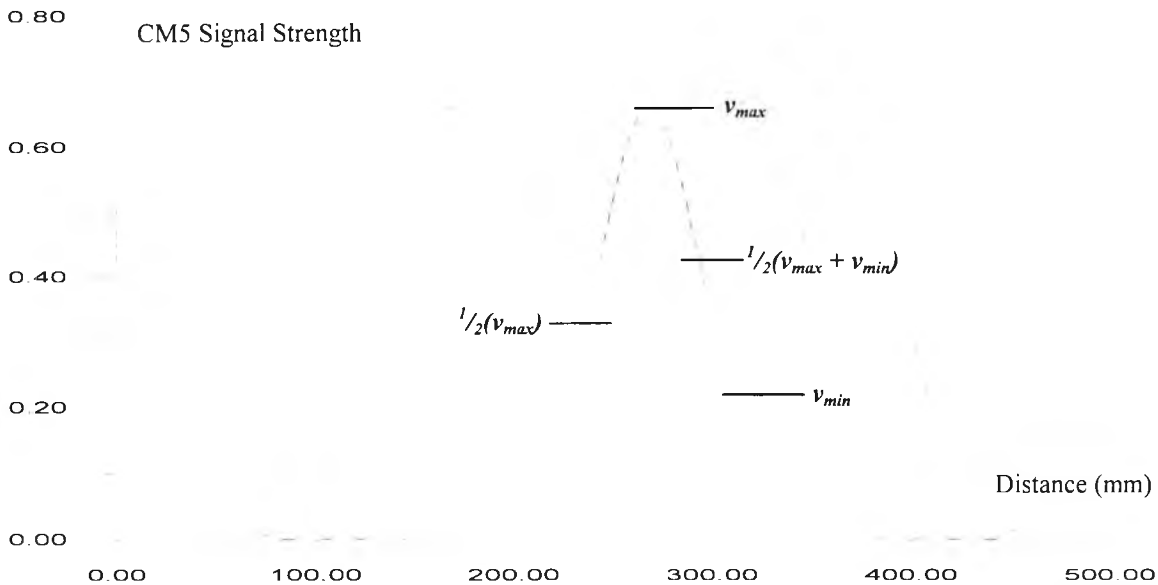
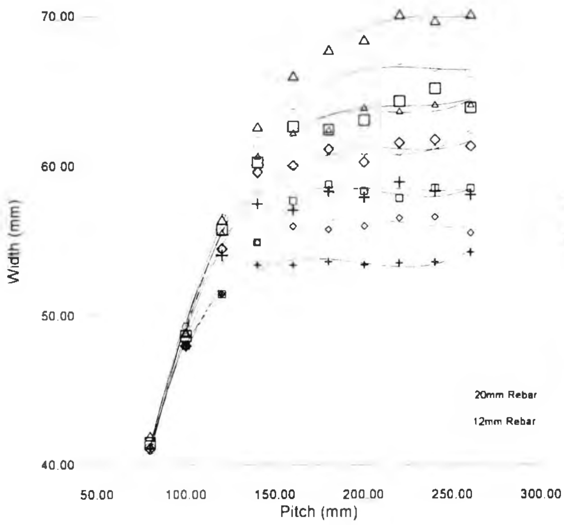
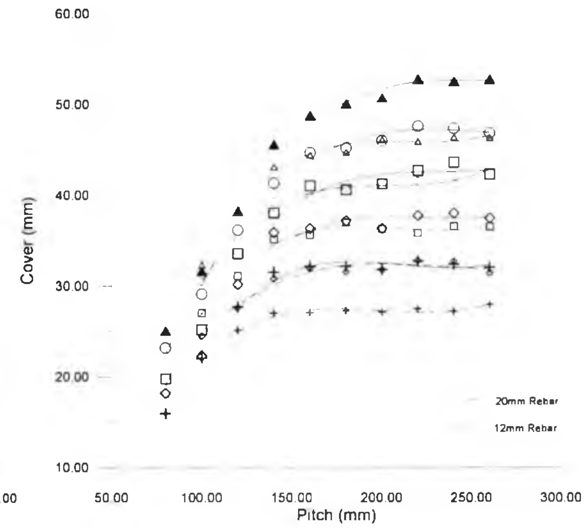


Figure 10.7 The effects of neighboring parallel re-bars on the traverse profile of the central re-bar.

With reference to the figure, it can be seen that the effects of the neighboring parallel re-bars on the central peak is to increase the span of the width. The effect becomes more pronounced when the pitch between re-bars decreases. In addition, the amplitude of the central peak increases due to this action.

If the width of the central peak is taken at half its peak height, the value would be 65.4 mm. This value is greater than that for the single peak, which in this case is 62.9 mm. If the width measurements were taken at the amplitude midway between the peak maximum and the trough minimum instead, the width value falls to 49.9 mm. This value is far narrower than the single re-bar profile. Figure 10.8(a) plots width values at $^1/_2(v_{max} + v_{min})$ for both 12mm and 20mm re-bars at covers ranging from about 25mm to 50mm against pitch, notice how rapidly the values of width drop for pitch values of less than 150mm. Figure 10.8(b) plots depth-of-cover, using the width values in Figure 10.8(a); against pitch. Here again, the trend is eminently similar. Thus, for pitches of about 150mm or less, the use of width values at $^1/_2(v_{max} + v_{min})$ to determine depth-of-cover is very unreliable.





(a) Plot of Width versus Pitch (b) Plot of Cover versus Pitch

Figure 10.8 The variation of width and cover against pitch for parallel 12mm and 20mm re-bars

Therefore, in order to determine depth-of-cover and re-bar size as in the case for a single re-bar, the traverse width to be taken for parallel re-bars would be between the two widths at $^1/_2(v_{max})$ and $^1/_2(v_{max} + v_{min})$. This leads to a hypothesis, that the signal reading at which traverse width should be taken at, is as follows:

$$v_{meas} = {^1/_2}(v_{max} + Qv_{min}) \qquad \text{Equation 10.8}$$

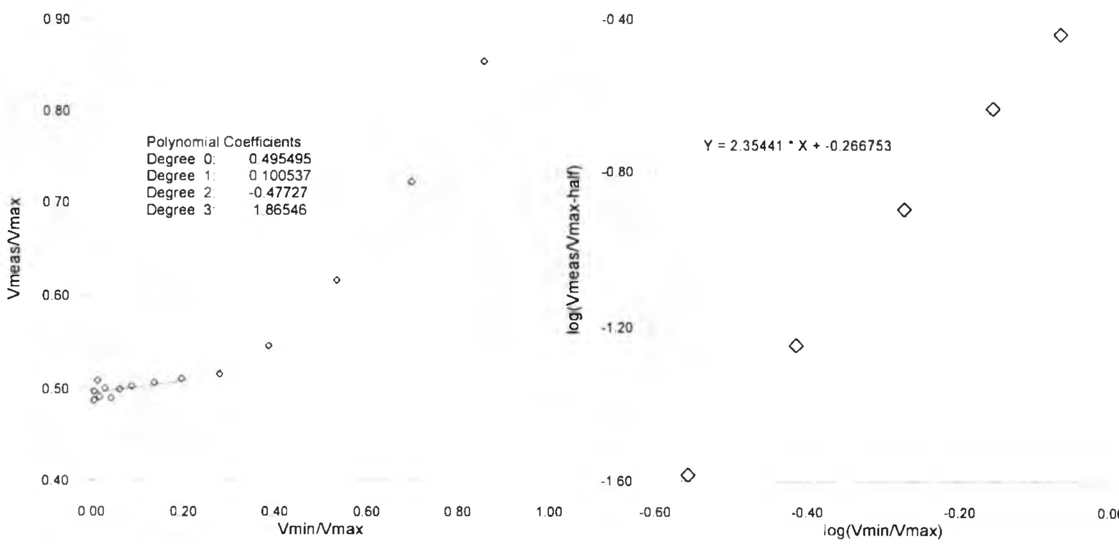
Where Q is a parameter between zero and one which will be determined experimentally and v_{meas} is the amplitude at which the width equalled that for an isolated re-bar. Note that the special cases of $Q = 0$ and $Q = 1$ correspond to the first two simple definitions of $^1/_2(v_{max})$ for single re-bars in isolation and $^1/_2(v_{max} + v_{min})$ for a single re-bar in the presence of traverse re-bars.

Attempts have been made to determine the value of Q empirically, but hopes that the value of Q is a simple constant proved unfounded, as demonstrated next. The logical step was to try to determine Q from Equation 10.8, and as the relevant independent variable in practice is the ratio v_{min}/v_{max} , the equation can be rewritten as:

$$v_{meas}/v_{max} = {^1/_2}\,Q(v_{min}/v_{max}) + {^1/_2} \qquad \text{Equation 10.9}$$

By plotting (v_{meas}/v_{max}) against (v_{min}/v_{max}) as in Figure 10.9(a), the value of Q is shown to increase with (v_{min}/v_{max}). To find if Q varies as a power of (v_{min}/v_{max}), a plot of log[(v_{meas} /v_{max}) - half] versus log[(v_{min} /v_{max})], where 'half' was either 0.49 or 0.5 because in some instances, the value of (v_{meas} /v_{max}) is less than 0.5 which would result in an indeterminate value when the log of it is taken. For wide pitches, (v_{meas} /v_{max}) - half is near zero and its logarithm would also be indeterminate; but for the four or five closest pitches, the slope is close to two (Figure 10.9(b)); implying that [Q . (v_{min} /v_{max})] is close to $(v_{min} /v_{max})^2$, hence $Q \sim (v_{min} /v_{max})$. Thus, Equation 10.9 can be rewritten as:

$$v_{meas} /v_{max} = {}^1/_2\, (v_{min} /v_{max})^2 + {}^1/_2 \qquad \text{Equation 10.10}$$



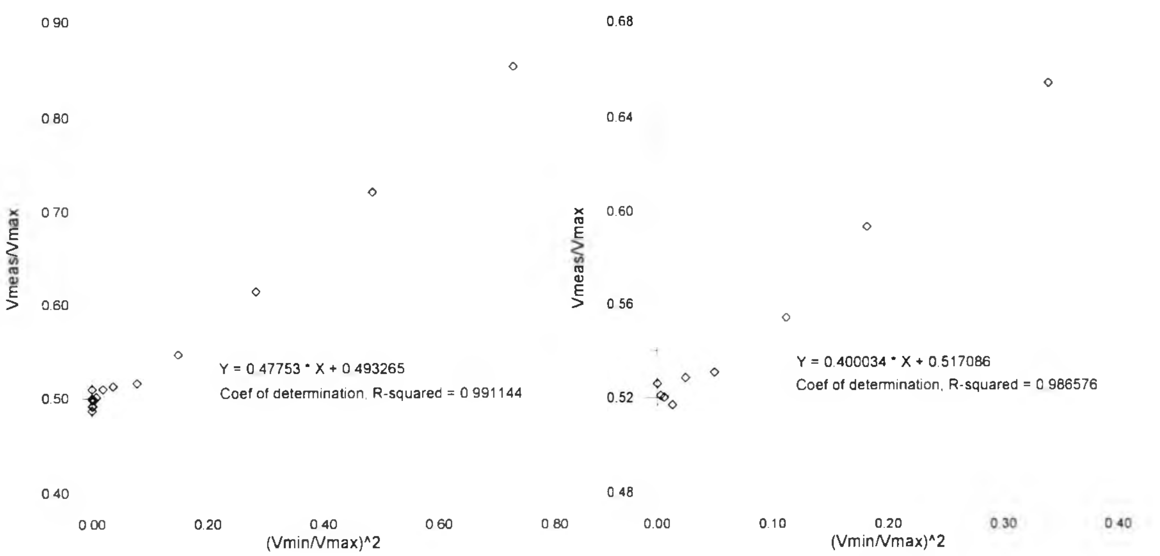
(a) Plot of v_{meas}/v_{max} vs. v_{min}/v_{max} (b) Plot of log(v_{meas}/v_{max} - half) vs. log(v_{min}/v_{max})

Figure 10.9 Plots to determine the value of Q using a 12mm re-bar at 36mm cover

To confirm that Q is (v_{min}/v_{max}), a plot of (v_{meas}/v_{max}) versus $(v_{min}/v_{max})^2$ was drawn and is shown in Figure 10.10(a). It shows a straight line of v_{meas}/v_{max} = $0.477(v_{min}/v_{max})^2$ + 0.493 with a correlation coefficient $r^2 = 0.991$. Clearly, the value of 0.493 should strictly be 0.5, so that $v_{meas} = {}^1/_2 v_{max}$ when $v_{min} = 0$. Whether the value of 0.477 should be rounded up to 0.5 for simplicity, or dropped down a bit to compensate for the increase in the 0.493 had to be looked into. A similar experiment was therefore, performed for a 20mm re-bar. The result is shown in Figure 10.10(b), giving a straight line of $v_{meas}/v_{max} = 0.400(v_{min}/v_{max})^2$ + 0.517 with a correlation coefficient $r^2 = 0.987$. Here, the value of 0.400 is marginally smaller than the expected 0.5 to suit Equation 10.10. The results probably meant that another constant, k (probably close to the value of one), had to be empirically determined as in Equation 10.11 if greater accuracy was to be obtained for v_{meas}.

$$v_{meas}/v_{max} = {}^{1}/_{2}[1 + k(v_{min}/v_{max})^{2}] \quad \text{Equation 10.11}$$

However, k is difficult to solve for in the same way, attempts to calculate a value for Q tended to give indeterminate values in too many cases.



(a) Plot for 12mm re-bars at 36mm cover (b) Plot for 20mm re-bars at 36mm cover

Figure 10.10 Plots of (v_{meas}/v_{max}) versus $(v_{min}/v_{max})^2$ for 12mm and 20mm re-bars

Therefore, instead of trying to determine the value of k empirically, it may be better to measure the width at v_{meas} by assuming v_{meas} to be:

$$v_{meas} = {}^{1}/_{2}v_{max}[1 + (v_{min}/v_{max})^{n}] \quad \text{Equation 10.12}$$

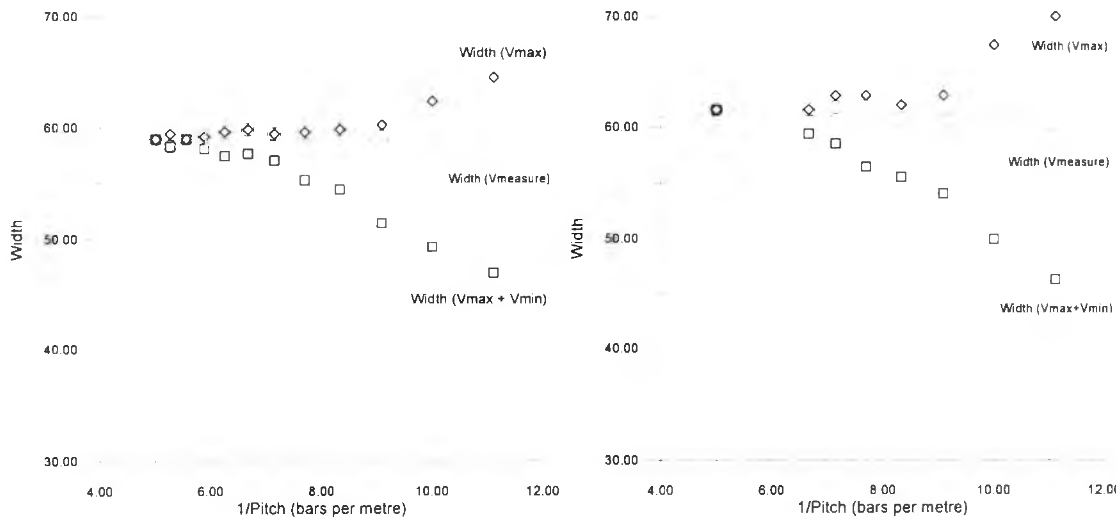
where $1.7 \leq n \leq 2.3$. The test would be to see which n value gave the most satisfactory overall answers to the determination of depth-of-cover and re-bar size. Tests were made on 12mm and 20mm re-bars at varying depth-of-cover. The full results of the test is included in the Appendix F-4, but is summarized in Table 10.2 for the 12mm re-bars case, and for $n = 2$, as this was found to give the best overall results. A $n = 2$ value was also found to provide the best overall results for the 20mm re-bars case.

Table 10.2 Results of using $v_{meas} = {}^{1}/_{2}v_{max}[1 + (v_{min}/v_{max})^{n}]$ with $n = 2$, in determining re-bar size and cover

Pitch	Actual Vmeas	Calc. Vmeas	W_{Vmax}	Dia-meter	Cover	$W_{(Vmax+Vmin)}$	W_{Vmeas}	Dia-meter	Cover
60	0.411	0.416	60.71	16	38.70	33.58	54.45	8	31.99
70	0.328	0.337	71.25	20	47.76	37.67	54.25	8	32.12
80	0.272	0.283	69.85	20	56.67	41.55	55.10	8	33.04
90	0.239	0.251	64.58	20	42.99	46.93	57.04	8	34.83
100	0.225	0.235	62.42	16	40.82	49.30	58.12	10	35.83
110	0.223	0.226	60.27	12	38.11	51.44	59.18	12	37.13
120	0.214	0.215	59.85	12	37.93	54.47	59.85	12	37.93
130	0.217	0.217	59.61	12	37.58	55.32	59.61	12	37.58
140	0.217	0.218	59.43	12	37.38	57.07	59.43	12	37.38
150	0.213	0.217	59.85	12	37.77	57.68	59.85	12	37.77
160	0.216	0.216	59.64	12	37.61	57.48	59.64	12	37.61
170	0.212	0.216	59.20	12	37.21	58.12	59.20	12	37.21
180	0.219	0.215	58.98	12	37.03	58.98	58.98	12	37.03
190	0.211	0.216	59.43	12	37.04	58.32	58.32	10	36.05
200	0.214	0.215	58.98	12	37.03	58.98	58.98	12	37.03

The last three columns in Table 10.2 lists the results of using Equation 10.11 ($v_{meas} = {}^{1}/_{2}v_{max}[1 + (v_{min}/v_{max})^{n}]$) and n value of two. The first three rows of the table meet the condition $v_{min} < {}^{1}/_{2}\ v_{max}$, and hence are expected to give erroneous results. Good results are obtained for pitches of 100mm and above, giving an estimate error of one re-bar size and ± 2mm error in depth-of-cover. A similar result of 90mm pitch and beyond, were obtained for the 20mm re-bars at varying covers of 36mm, 41mm and 46mm (see Appendix F-4).

Figure 10.11 plots the three possible estimates of width, W_{Vmax}, $W_{(Vmax+Vmin)}$, and W_{Vmeas} versus 1/Pitch for both the 12mm (Figure 10.11 (a)) and 20mm (Figure 10.11 (b)) re-bars at 36mm cover. The horizontal dashed line on both plots represent the width of a traverse over a single re-bar. It can be seen that W_{Vmeas} is considerably more reliable than either of the two uncompensated widths.



(a) Plot for 12mm re-bars at 36mm cover (b) Plot for 20mm re-bars at 36mm cover

Figure 10.11 Plots of Width versus 1/Pitch (bars per meter) for 12mm and 20mm re-bars

10.6 Effects of Overlapping Re-bars

As yet, the Traverse Profile Width Method is not able to estimate re-bar size and depth-of-cover for overlapping re-bars. Nevertheless, if the presence of re-bars can be pre-determined, the Traverse Profile Width Method could be compensated to take this into account. This requires further investigation, unfortunately, beyond the coverage of this thesis. However, if the presence of overlapping re-bars can be pre-determined, those areas could be avoided, and the nearest vicinity to it could be inspected for when the lapping terminates. When this is found, the Traverse Profile Width Method could then be employed to estimate re-bar size and cover for a single re-bar.

The effects of overlapping re-bars on the CM5 covermeter reading, is shown in Figure 10.12. From looking at the traverse profile reading, it is not at all possible to determine, if in fact, there exist overlapping re-bars. Hence, another method of determining overlapping has to be investigated.

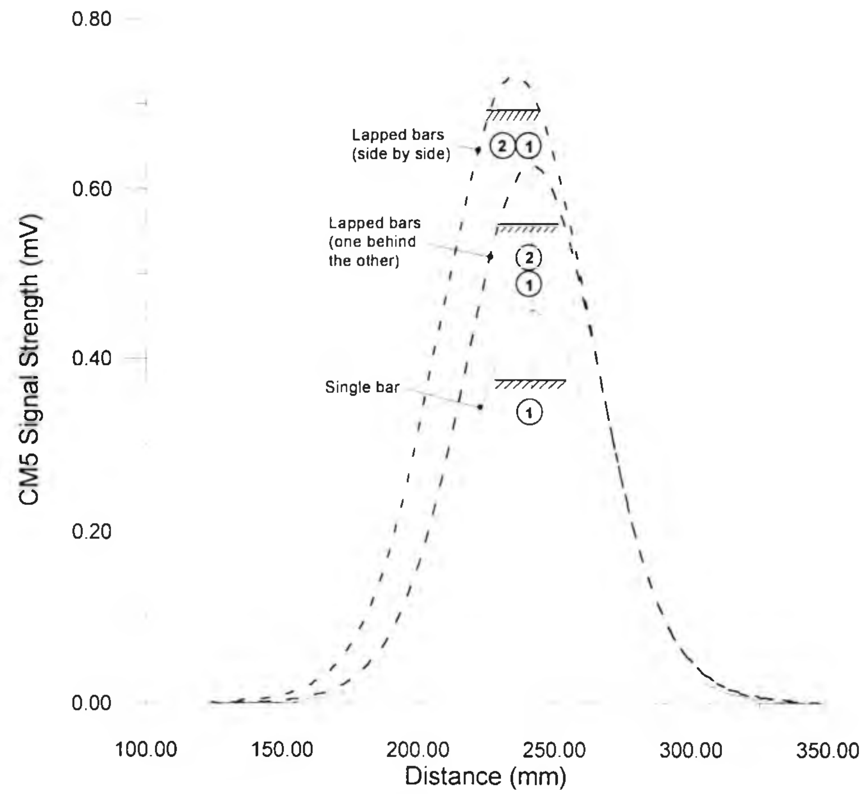
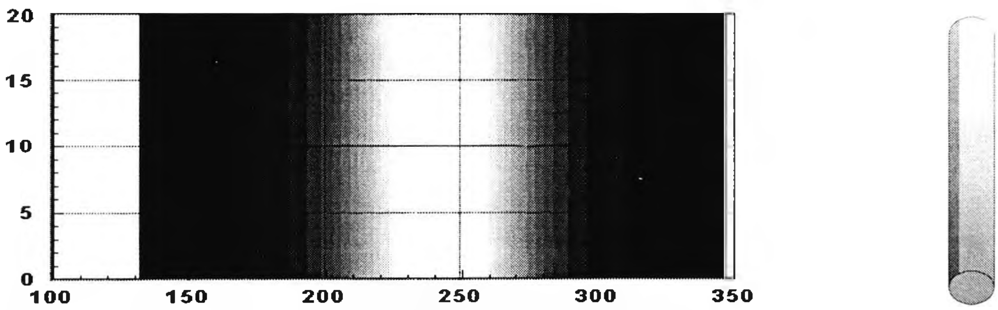
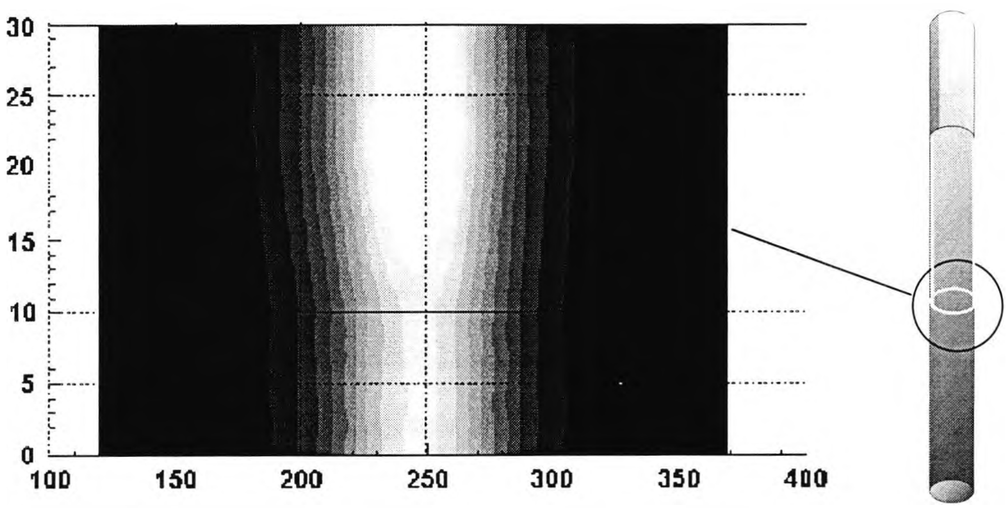


Figure 10.12 Variation of Signal Strength for Single and Lapped Re-bars vs. Distance (for 12mm re-bars at 35mm Depth-of-Cover)

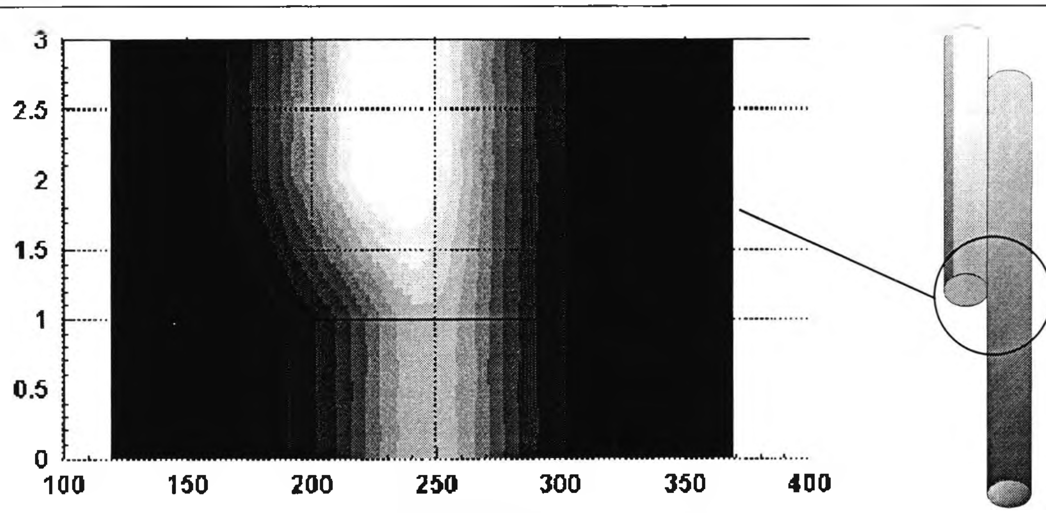
To determine the occurrence of lapping in re-bars, the author proposes, performing an area sweep of the region under investigation, using a covermeter to obtain an 'x-ray' like image of the scanned surface. Figure 10.13 shows some sample scans, obtained from using a CROCUS robot and a CM5 covermeter, on two types of lapping configurations. Referring to the scanned images of Figure 10.13, overlapping re-bars are clearly visible.



(a) A surface area scan on a single 12mm re-bar at 35mm cover



(b) A surface area scan on a pair of 16mm overlapping re-bar (one above the other) at a cover of 40mm



(c) A surface area scan on a pair of 16mm lapping re-bar (side-by-side) at a over of 40mm

Figure 10.13 Two configurations of overlapping re-bars and their respective scanned images

10.6 Conclusion

This chapter covered the theory and experiments needed in obtaining equations and a set of values (Table 10.1) that could be used by a CM5 covermeter to estimate both, re-bar size and depth-of-cover. The first equation is based on a new traverse profile theory. The theory is based on first principles of variation of covermeter signal strength with distance, resulting in the equation $z = (\sqrt[3]{[A(r)/v]} - R^2)^{1/2}$.

The second equation, $z = 1.799\ W_{1/2} - 63.31$; comes from the Traverse Profile Width Method of Section 10.3. Again this is specific to the CM5 covermeter, but details are again provided on how they were determined, so that they may be applied to other makes of covermeters. The effects of neighboring re-bars were also investigated on the proposed methodology for estimating both, re-bar size and depth-of-cover. Here, empirical experiments were performed to obtain the best voltage signal position (v_{meas}) in order to obtain the width value (W_{Vmeas}) that was needed by the methodology, in determining the two unknowns. The equation, $v_{meas} = {}^{1}/_{2}v_{max}[1 + (v_{min}/v_{max})^2]$ to determine W_{Vmeas}, were found to be effective at pitches greater or equal to 100mm (see Table 10.2). The accuracy of the estimations by the Traverse Profile Width Method often fall well within the expected ±5% or 2mm (BS1881:204:1988) range, whichever is greater; and the predicted re-bar size often to within one re-bar size. Full listings are provided in Appendix F-3. A sample from a random test is enclosed below, in Table 10.3.

Table 10.3 Results of random testing on single 12mm, 16mm and 20mm re-bars

True Diameter(mm)	True Cover (mm)	Estimated Cover (mm)	Cover Estimate % Error	Predicted Re-bar Size (mm)
12	29.70	30.20	1.68	12
12	32.70	32.68	-0.06	12
12	37.70	38.06	0.95	12
12	42.70	44.12	3.33	12
16	30.90	31.51	1.97	16
16	33.90	34.89	2.92	16
16	38.90	38.69	-0.54	16
16	43.90	44.91	2.30	16
20	30.80	31.73	3.02	20
20	33.80	34.35	1.63	20
20	39.80	40.79	2.49	20
20	44.80	45.34	1.21	20

The next chapter (Part 3) discusses a case study, implementing the Traverse Profile Width Method discussed in this chapter, and the HMI guidelines in Part 1 of this thesis.

11. CURIO Software

11.1 Introduction

This chapter discusses the work involved in integrating the research from Part 1 (guidelines) and Part 2 of this thesis, in developing a software application for controlling CURIO, and operating the proposed NDT inspection devices (Appendix C). The CURIO software development process is currently in its third phase, awaiting completion of a working prototype of CURIO; enabling current developments to be tested. Three phases of development are described in turn. This chapter is intended as a case study on both the software development and covermeter automation theory. This chapter also provides detail description on the functionality of the latest HMI prototype, and how a typical covermeter inspection is conducted with it.

As the CURIO robot was not available during the software development process of the CURIO software, a CROCUS gantry robot was used in its place. Descriptions of both robots are provided in Appendix B. These robots have very similar arrangement of motion axes.

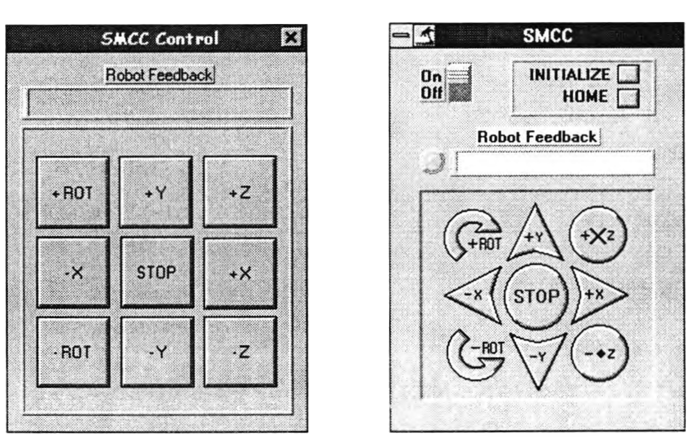
11.2 Phase I - Basic Functionality

The first phase in the development process of the CURIO software involved developing the basic functional aspects of the application. The G-language provided in LabView, was utilized in programming all applications within this project. LabView was chosen because of its strength in handling data acquisition, which was requisite for the NDT devices to be implemented on CURIO. However, due to some complications encountered during the development phase, some applications were created in the C-language for debugging purposes.

The goal of Phase I, was computerization of both the CROCUS robot, and the CM5 covermeter. For the robot, the work involved developing a software motion control panel. An initial version of this is depicted in Figure 11.1(a). Once this was able to control the basic motions of the robot successfully, the author began implementing the guidelines worked out in chapters 3 to 5. The result of the initial HMI improvements are depicted in Figure 11.1(b). These HMI improvements are discussed in Phase III (Section 11.4), which concentrates on the HMI development of the CURIO software.

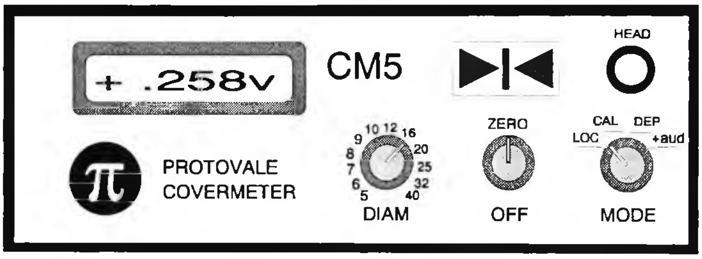
Following this, work started on the computerization of the covermeter. This involved building a software control panel for the covermeter. Figure 11.2(a) depicts an illustration of the hardware front panel of the actual covermeter, while Figure 11.2(b) depicts the computerized version of it. The benefits of the computerized software version over that of the hardware covermeter include the ability to data-log covermeter signal readings, and to display these graphically as a plot in real-time.

Succeeding the two software developments, the author merged both programs into a single application. This provides the covermeter with positional information from the robot. Figure 11.3 depicts the result of the merger, after having gone through extensive modifications to the control panel. The software depicted in the figure, was used extensively in performing early experiments to the Traverse Profile Width Method of Chapter 10.

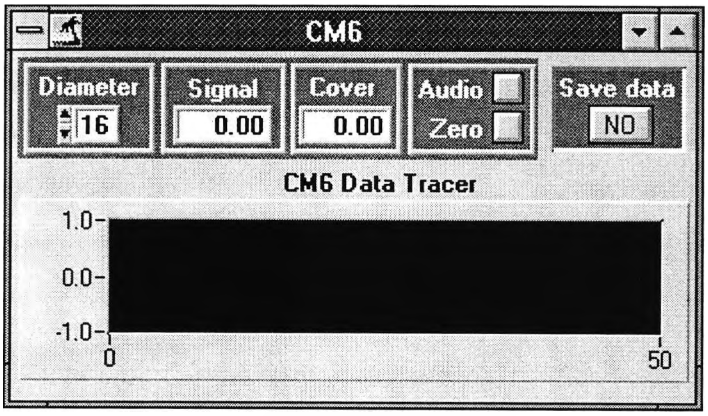


(a) Initial version (b) Improved version

Figure 11.1 Initial designs of the software Control Panels for the CROCUS gantry robot



(a) Hardware Front Panel



(b) Software Control Panel

Figure 11.2 Hardware and Software version of the CM5 covermeter

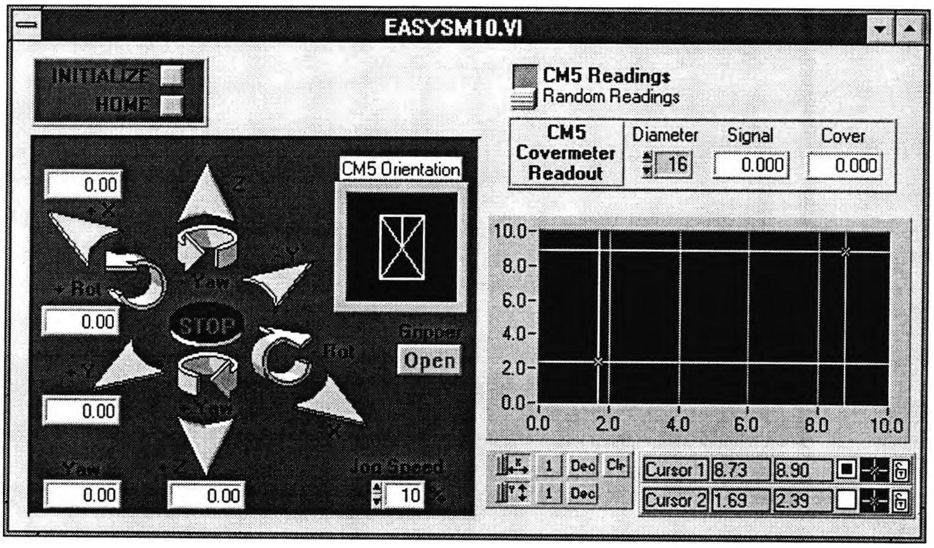


Figure 11.3 An application used in performing the early experiments required in the development of the Traverse Profile Width Method

11.3 Phase II - Building the Application

The goal in Phase II, was to develop an application that would control the robot in performing a covermeter inspection, using the Traverse Profile Width Method of Chapter 10. In addition to using the Traverse Profile Width Method, the author has incorporated a new feature to the application; one that would allow users to plot covermeter readings with respect to position. With this facility, covermeter scans are shown to produce images of re-bars in concrete. This feature provides operators with more information about the test site, than would be available from using the covermeter in a manual inspection. The result of the software, is depicted in Figure 11.4. A sample graphical plot, which the author refers to as an 'X-ray' re-bar image, is depicted in the right-hand half of the figure. This is described further, in section 11.3.2. The next section, describes the application of the Traverse Profile Width Method.

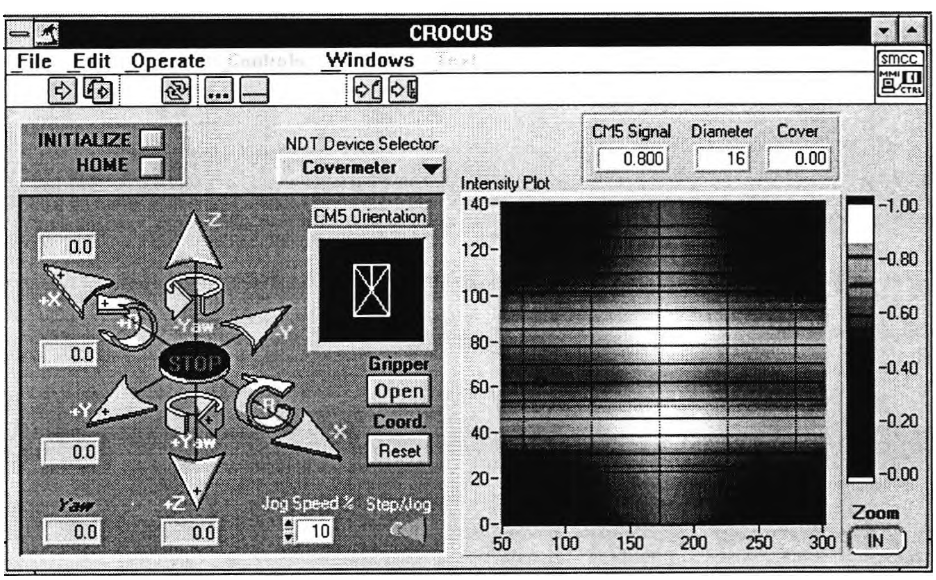


Figure 11.4 A CROCUS software Control Panel, incorporating a working model of the Traverse Profile Width Method

11.3.1 Application of the Traverse Profile Width Method

As worked out in Chapter 10, the traverse profile width method uses the response of the CM5 covermeter as the search probe is scanned across a bar to determine it's depth. As a result, by using the covermeter initially to indicate signal strength, the distance to the bar's center can be determined directly without prior knowledge of bar size. By next using the instrument as a conventional covermeter, the bar diameter can be deduced as being that value at which the indicated cover plus half the diameter equals the previously determined distance to center. This technique can be applied to any covermeter that is capable of indicating signal strength.

For easy reference, all equations and values used in the application are summarized below:

$$z = 1.799\, W_{Vmeas} - 63.318 \qquad \text{Equation 11.1}$$

$$V_{meas} = {}^{1}/_{2} v_{max} [1 + (v_{min}/v_{max})^2] \qquad \text{Equation 11.2}$$

$$z = (\sqrt[3]{[A(r) / v_{max}]} - R^2)^{1/2} \qquad \text{Equation 11..3}$$

$$z = c + r \qquad \text{Equation 11.4}$$

where W_{Vmeas} = traverse profile width at V_{meas} (mm)

v_{max} = peak voltage of the traverse profile (mV)

c = depth-of-cover (mm)

r = re-bar radius (mm)

Bar size	Slope ($1/\sqrt[3]{A(r)}$)	Intercept	R^2 (Coil Dimension)
8mm	4.77e-04	4.60e-01	964
10mm	4.59e-04	4.47e-01	973
12mm	4.10e-04	4.07e-01	994
16mm	3.51e-04	3.44e-01	980
20mm	3.15e-04	3.26e-01	1030

Table 11.1 Experimental results of $1/\sqrt[3]{A(r)}$ and R^2 for five different re-bar sizes

In the software of Figure 11.4, Equations 11.1 and 11.2 are first used to obtain a z value. This value of z is then compared with the z values obtained from Equation 11.3, which in itself, uses the values in Table 11.1. From Equation 11.3 and Table 11.1, five z values are obtained. The z value closest to the initial z value, obtained from Equation 11.1 and 11.2, provides an estimate of re-bar size, $\boldsymbol{r}$. Depth-of-cover can then be determined, by using the $\boldsymbol{r}$ and z values in Equation 11.4.

The process of determining the initial value of W_{Vmeas}, and hence, the estimation of re-bar size and depth-of-cover, as described above; has been fully automated in the application depicted in Figure 11.4. The graphical representation of the estimation process of re-bar size and depth-of-cover, is depicted in Figure 11.5.

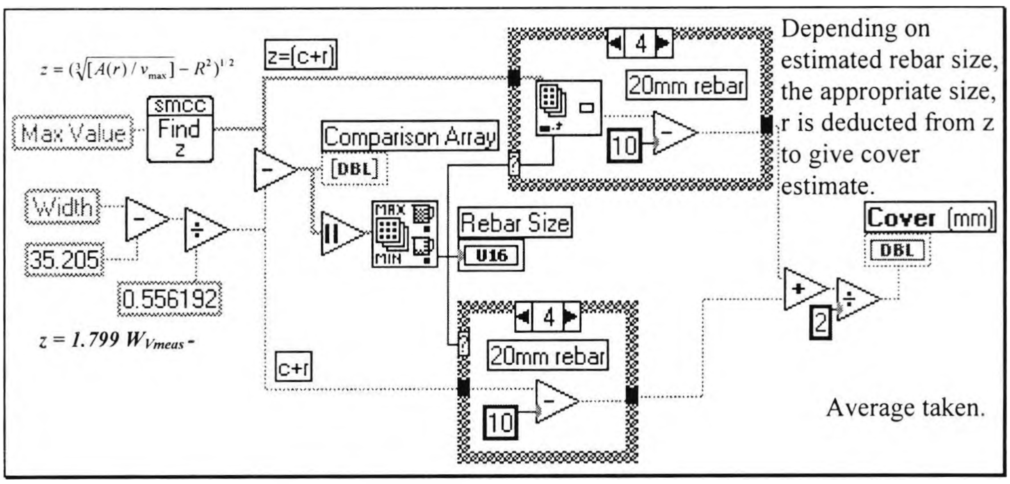


Figure 11.5 Graphical representation of the process undertaken in the estimation of re-bar size and depth-of-cover

11.3.2 Application of Re-bar Images

The ability to scan a surface to obtain an 'x-ray' like image of embedded re-bars, provide operators with a simple method of determining re-bar position, orientation, and in some instances; detailed re-bar configuration. Figures 11.6(a) and 11.6(b) show the result of two horizontal re-bar scans, obtained using the application depicted in Figure 11.4. Both these images provide a good representation of the embedded vertical re-bars; however, due to the directional nature of the electro-magnetic covermeter, Figure 11.6(b) produces two horizontal representations of the single horizontal re-bar. The true position of the horizontal re-bar, is actually at the center of the two representations. In practice, the result of horizontal scans, as depicted in the two figures, would only be used to determine the position of vertical re-bars. To determine the position of horizontal re-bars, the covermeter heads, as depicted in the figures would be rotated by 90°. Performing a vertical sweep of the area, would then produce an image of the horizontal re-bars. Figure 10.13 of Chapter 10, provide two other sample re-bar images that are commonly encountered in concrete structures. The images show details of two different lapping re-bar configurations.

It should be noted, that the re-bar images discussed thus far are still representations of covermeter signal strength with respect to position; and are therefore, not true representations of the detected re-bars. The re-bar images however, do provide information about the various re-bar locations and configurations. Therefore, using this information and the estimations from the Traverse Profile Width Method, the re-bar images can be manipulated to depict true re-bar sizes and depth-of-cover. The latter could be portrayed in variations of gray, as in an x-ray. Dark gray would indicate deep cover and white, shallow. This will be discussed further in Phase III.

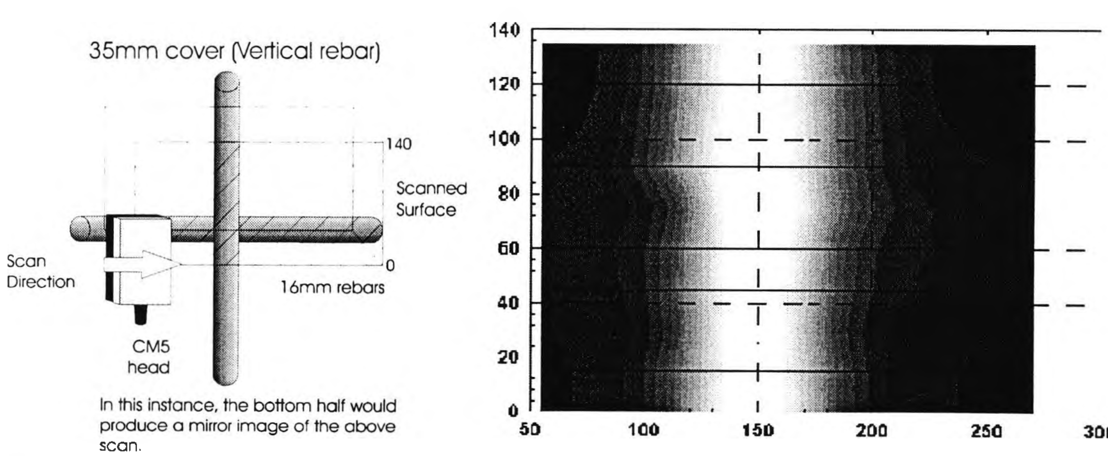


Figure 11.6(a) 'X-ray' image of cross re-bars with the vertical re-bar being closer to the surface

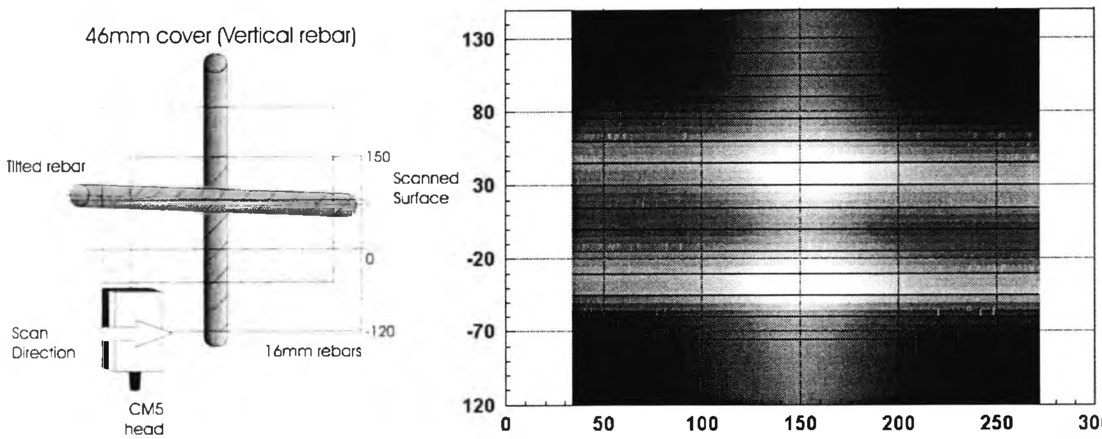


Figure 11.6(b) 'X-ray' image of cross re-bars with the horizontal re-bar being closer to the surface

11.4 Phase III - Designing the CURIO HMI

In Phase I and Phase II, developments concentrated on the functional aspects of the CROCUS robot and the CM5 covermeter. The goal in Phase III, is to port these developments onto the CURIO robot, extend the coverage to include the other NDT devices discussed in Appendix D, and to apply the observations of the HMI studies in Part 1 of the thesis.

11.4.1 Goals

The main goal of the CURIO software, is to develop an application that will allow operators to easily perform various tele-operated NDT inspections using the CURIO robot. The proposed inspection setup is depicted in Figure 11.7. The HMI control center will be at ground level, while the robot is suspended by a power winch, that allows it to be lowered down the side of a building. Inspection processes will likely be out of sight of the operator, hence the requirement for tele-operation.

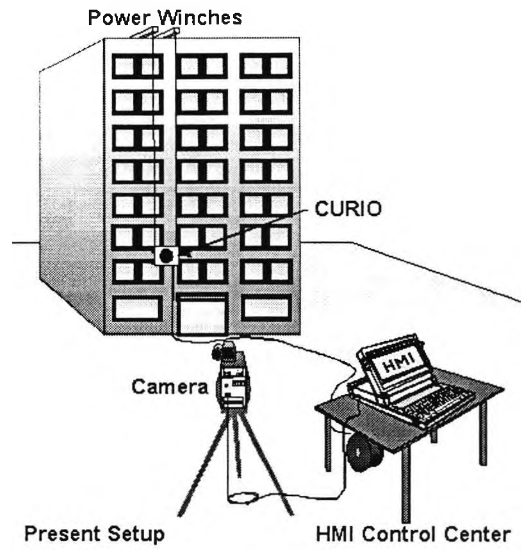


Figure 11.7 Current CURIO Inspection Setup

The author's HMI goal, illustrated in Figure 11.8, is to make the process of interacting with the HMI and CURIO as transparent as possible. By doing so, the author hopes to create a directness in performing the various inspection processes, and hence make the system easy to use.

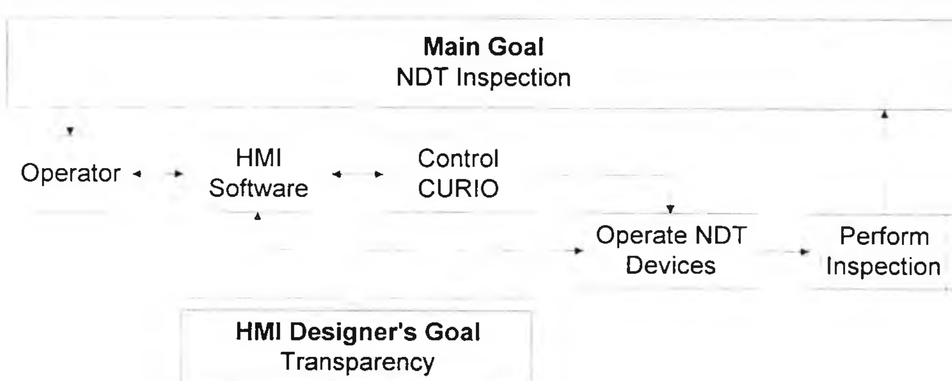


Figure 11.8 CURIO Application Goals and the Author's HMI Goal

11.4.2 HMI Software Design

The HMI software design, is based on the iceberg chart covered in Chapter 3 (Figure 3.4). The chart defines the conceptual model of a designer, and is divided into three areas; object relationships, feel and look. The next three sections covers these in turn.

11.4.2.1 Object Relationships

This part of the iceberg is made up of properties, behaviors and functionalities of objects contained within an application; and the relationships these objects hold with each other, and eventually the HMI. Object relationships govern how an application is structured, and it provides users with a framework of how an application is organized, both internally and at the interface. To build the object relationships of the CURIO software; the author started with the inspection requirements of the various NDTs (Table 11.2). When this was established, the author related them to how CURIO could be used in performing the various inspections. Other object relationship considerations include the ground control computer, which itself will consist of a common keyboard and mouse as input devices; and a monitor as an output device.

The relationship between the HMI software, the robot and the proposed NDT devices, are depicted in Figure 11.9. With reference to the figure, three main groups are apparent in designing the HMI control panel. These are coded alphabetically in the figure. The A, represents a panel to depict the control and feedback of the robot; B, a panel for the control and feedback of the NDT devices; and C, an area where the result from NDT testing is collated with positional information. The latter is one of the greatest benefits of incorporating the various NDT devices onto CURIO, as it is capable of presenting the various NDT test results, in an area that is a representation of the inspection site. As all NDT inspections are with regard to the same site, a comparison between any of the inspection results can easily be made.

Table 11.2 CURIO NDT Software - Input and Output Task Requirements

NDT Hardware	Inspection Test Element	Input	Output	Factors of Concern
Video Camera	Visual defects, dimensions, cracks, etc.	Static, pan, zoom. (A)	Still image, moving images.	Lighting.
Covermeter	Re-bar location & depth of cover.	Close proximity parallel plane trans. & rotation. (L/ A)	Re-bar size estimation, depth of cover & visual image of re-bars.	Neighboring re-bars and other electromagnetic conducting material.
Impulse Radar	Re-bar location, delamination, voids, etc.	As for covermeter + speed control. (L/ A)	Visual image.	
Thermographer	Delamination, moisture, voids, etc.	As for covermeter + speed control. (L/ A)	Visual image.	To avoid extraneous heat source & wind.
Acoustic Hammer	Delamination, voids, etc.	Two elements, normal strike and contact. (P)	Single rebound readings.	Holding transducer on surface while creating impact.
Schmidt Hammer	Hardness.	Contact normal with held reaction. (P)	Single hardness readings.	Susceptible to surface hardening carbonation, shallow re-bars, etc.
Half-Cell	Re-bar corrosion.	Contact point readings. (P/ L/ A)	Point readings giving rise to contour plots.	Obtaining electrical continuity & wetting of surface.
Resistivity Meter	Re-bar corrosion.	Contact point readings. (P/ L/ A)	Point readings giving rise to contour plots.	Susceptible to temperature, moisture & salt content.
Laser Profiler	Surface & edge damage.	Parallel proximity to surface sweep. (L/ A)	Graphical profile reading.	

P = Point / L = Line / A = Area

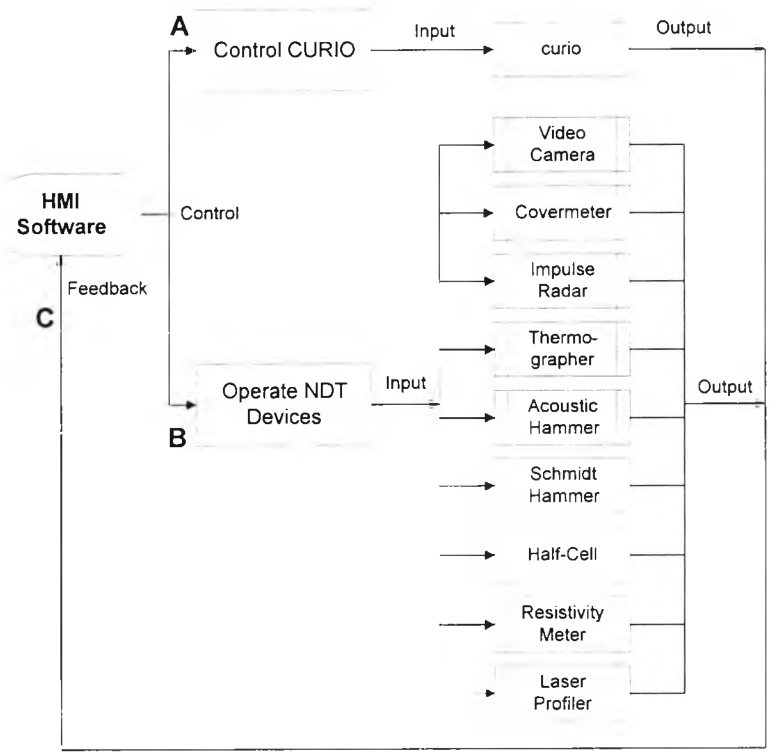


Figure 11.9 'Top-level' object relationships of the CURIO software

A few points are noted concerning these groups. Firstly, unless an inspection process has been run fully automated, the CURIO control and feedback panel should remain visible at all times. Secondly, as the robot is designed to perform a single inspection at a time; there is no need to display all NDT device panels. Thirdly, the graphical output from the NDT tests represents the test site; and this feature applies to all the NDT devices. The graphical output area is thus a permanent feature of the interface. This area will be referred to as the Workspace.

11.4.2.2 Look

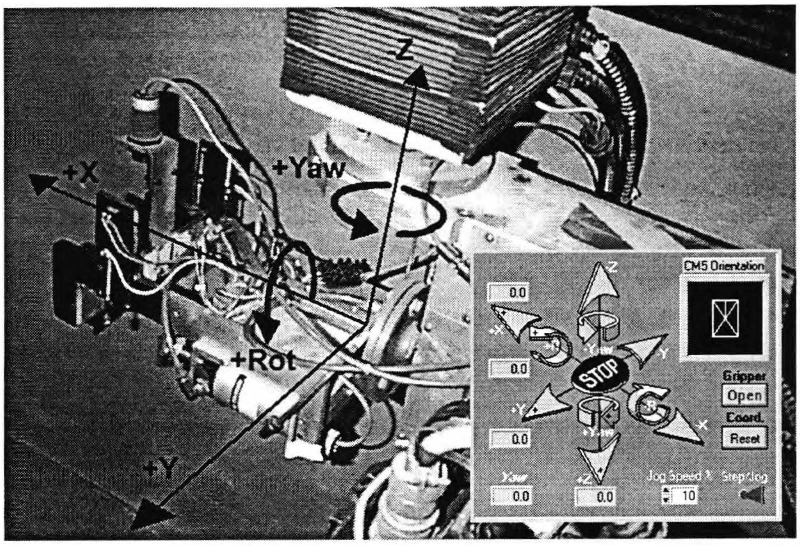
Part 1 of this thesis, has three chapters that consider the 'look' of an application; they include the use of colour (Chapter 4), the design of icons (Chapter 5), and HMI layout design (Chapter 6). The CURIO HMI has been derived with regard to the observations made in these chapters.

As the HMI is to be used as a tele-operated control panel, to control both the CURIO robot and various NDT inspection devices, the author uses representational icons to denote controls that resemble their physical counterparts. The representational icons used in the HMI design resemble switches, slider-bars, buttons, LED displays and knobs. These are often encountered on household, as well as industrial instruments, and are therefore, more likely to promote a more familiar interface.

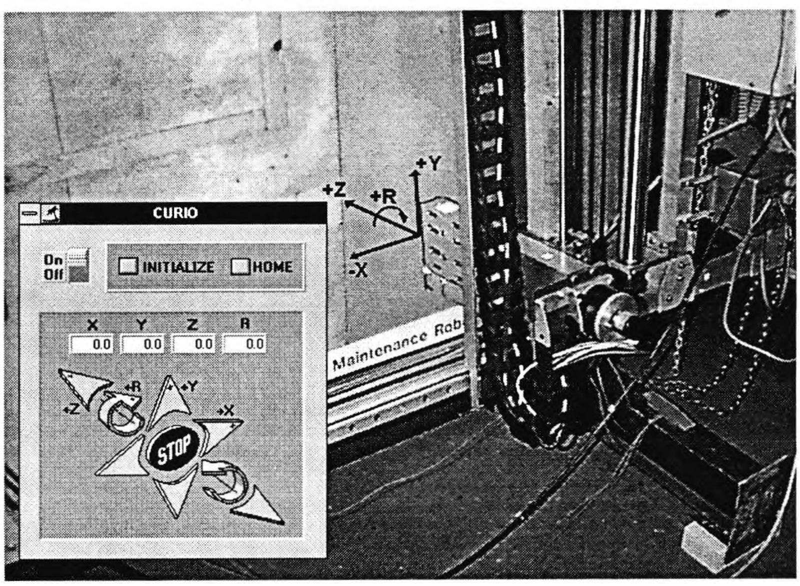
11.4.2.2.1 CURIO Motion Control Panel

To port the developments of the CROCUS software onto CURIO, the author redesigned the robot control panel of the former, to accommodate the motion axes of the latter, as illustrated in Figure 11.10. In both panels, the motion icons (controls) are laid out in a 3-dimensional (3-D) perspective, to correspond to their respective motion axes (Figure 11.10). The appearances of these icons have also been designed to visually depict their motions.

The axial motion buttons behave like ordinary buttons with two states, on and off. The rotary motion buttons, however, have been designed to depict their rotary motions as illustrated in Figure 11.11, but with the same on and off states. The advantages of having such animated sequences are twofold. Firstly, animation provides operators with a visual feedback when a button is depressed. Secondly, the state of these buttons acts as a status indicator; as it provides users with knowledge as to whether an axis is in motion. Taking the plus rotation button as an example, when a user depresses this button, it provides a visual feedback by rotating in an anti-clockwise direction. The robot, responds to this action by rotating its end-effector in a corresponding fashion. If the robot was performing a minus rotation at the time, the minus rotation button will pop back up and a plus rotation is performed.



(a) CROCUS robot control panel



(b) CURIO robot control panel

Figure 11.10 3-dimensional motion control panels

Figure 11.11 A few animated sequences from the 3-D robot control panels depicted above

The author also ported the 2-dimensional (2-D) layout motion control panel of the CROCUS robot (Figure 11.1(b)) onto CURIO. The two, however, are visually identical, as the latter did not take into account the robot's yaw motion. In a survey conducted by the author (Appendix H), two thirds of those surveyed, preferred the 3-D control panel, as they found it was easier to interpret the various motions of the robot. The other third, however, preferred the 2-D control panel because of its simplicity, and half of these were women. Study on the difference between men and women indicates, that the latter are often better in visualizing spatial information. The initial finding in this survey, that women prefer the 2-D control panel might very well support this claim. However, a more extensive survey would have to be conducted to confirm this.

As the majority were for the 3-D motion control panel, the author incorporated it into the CURIO software, as depicted in Figure 11.12. This panel, however, is not without its drawbacks. With high speed motions, or with motions that require frequent opposing moves (e.g., +Z and then -Z), the 3-D control panel design was found to be inappropriate. The large traverse distance between some of the opposing moves produces slower responses, and with repeated to and fro motions, fatigue. To reduce the effects of this problem, the author redesigned the layout of the control panel, as depicted in Figure 11.13. A drawback of the 3-D control panel, in comparison to the 2-D version, that cannot be remedied, however, is the larger screen space the former takes.

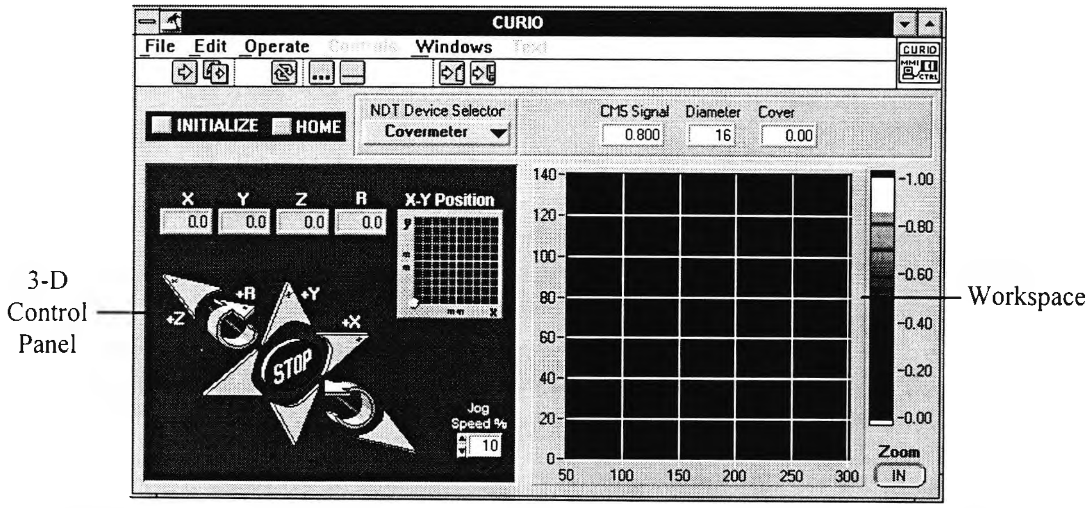


Figure 11.12 The initial CURIO HMI control panel, modified from the last CROCUS version

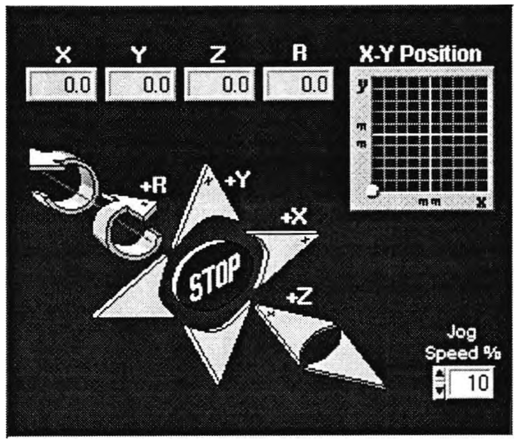


Figure 11.13 Modified control panel layout (see Figure 11.12)

From analyzing this software in meeting the author's goal of creating a transparent interface, the author found that operators are being given the impression of manipulating a robot in performing the various NDT inspections. This removed the directness the author had intended, whereby operators should feel they are performing an inspection directly. Another drawback of the design was the constant switching of attention, that was needed between the 3-D control panel and the Workspace during an inspection process. This non-compliance to the transparency goal comes at no surprise, however, as the CROCUS software had very different design goals.

To achieve the goal of transparency, the author redesigned the CURIO software using the object relationships of Section 11.4.1. The final version is depicted in Figure 11.14, and a colour version is provided in Colour Plate 1. Its appearance is very different to that of Figure 11.12; as the previously prominent 3-D motion control panel has been removed. In the latest HMI, the motion control panel of the robot is in-built into the Workspace (see Figure 11.14). This eliminates the problem of having to shift one's attention from the robot control panel to the Workspace, and vice-versa. It also promotes a more direct approach to inspection. However, the author does provide the operator with an option to call up the previously designed 2-D and 3-D control panels (Figure 11.15). These control panels are recommended for controlling the CURIO robot, while the Workspace motion icon is recommended for inspection use. The 3-D motion control panel has been redesigned with a gradient background to further enhance depth perception (see Section 2.2.3).

By reducing the motion controls of the robot to its most basic, and frequently used motions, as in the Workspace motion icon, the author allows the operator to focus on the inspection process. This in turn minimizes the sense that one is manipulating a robot and hence, produces a more direct approach to inspection. The size of this motion icon has to be studied to determine its most effective size. This awaits a working prototype of CURIO.

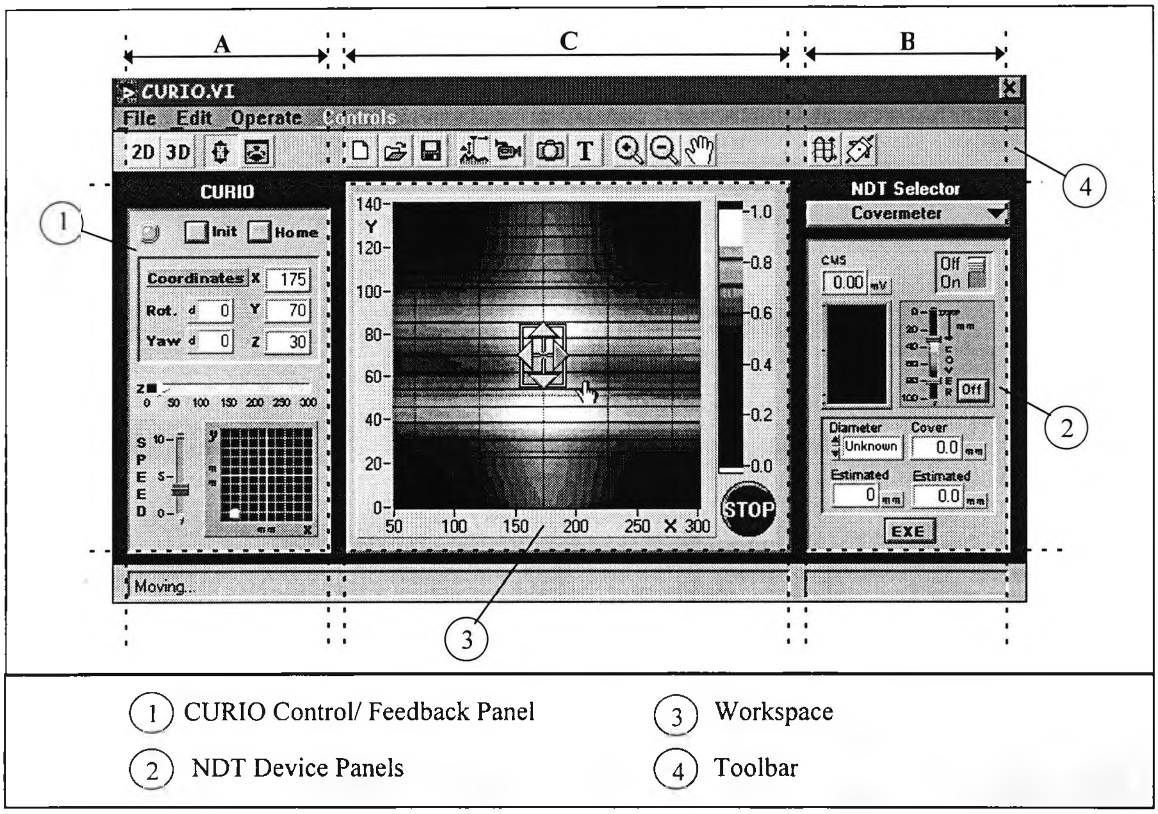


Figure 11.14 The latest CURIO robot control panel

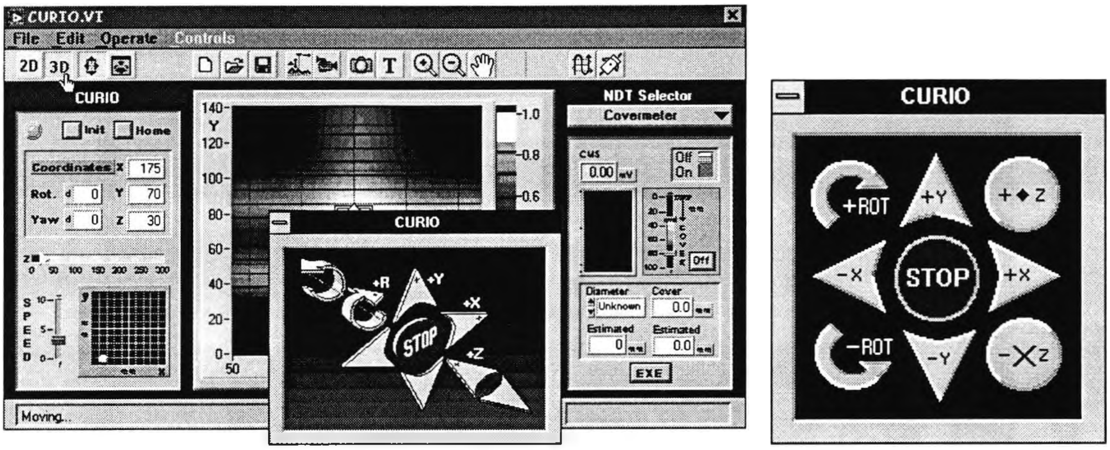


Figure 11.15 Option to call up a 2-D or 3-D robotic control panel. The 2-D motion control panel is shown larger for clarity

In the event that another motion is required, the author provides extra motion icons that operators can call up in its place. The operator does this by right mouse clicking the X-Y motion icon to bring up a menu of icons. From this, an operator can select the required motion icon. The various motion icons and their respective description, are provided in Figure 11.17.

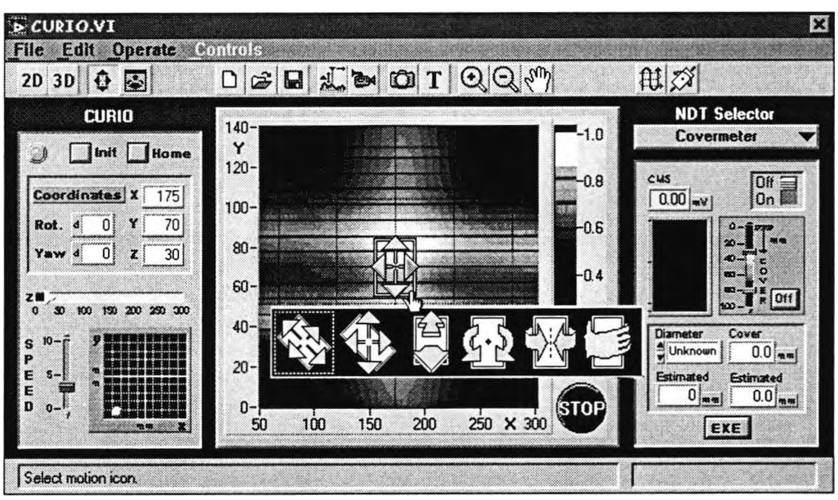
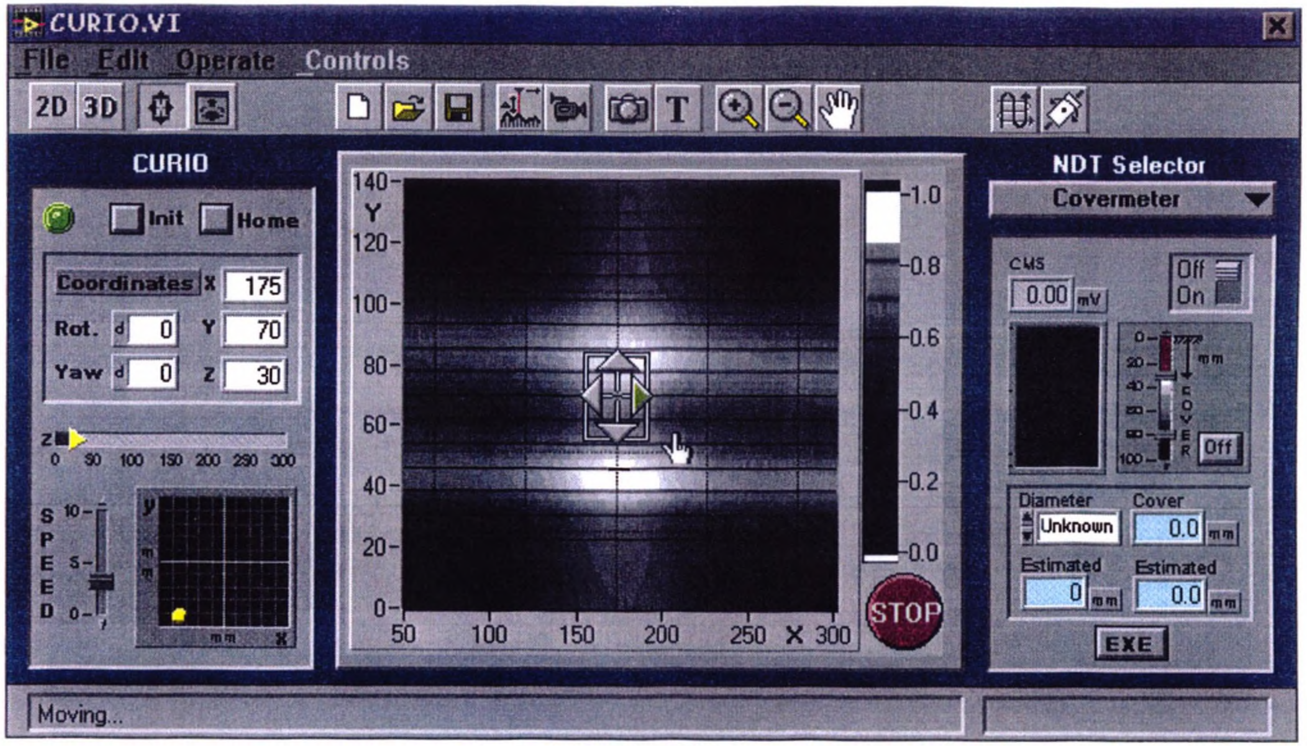
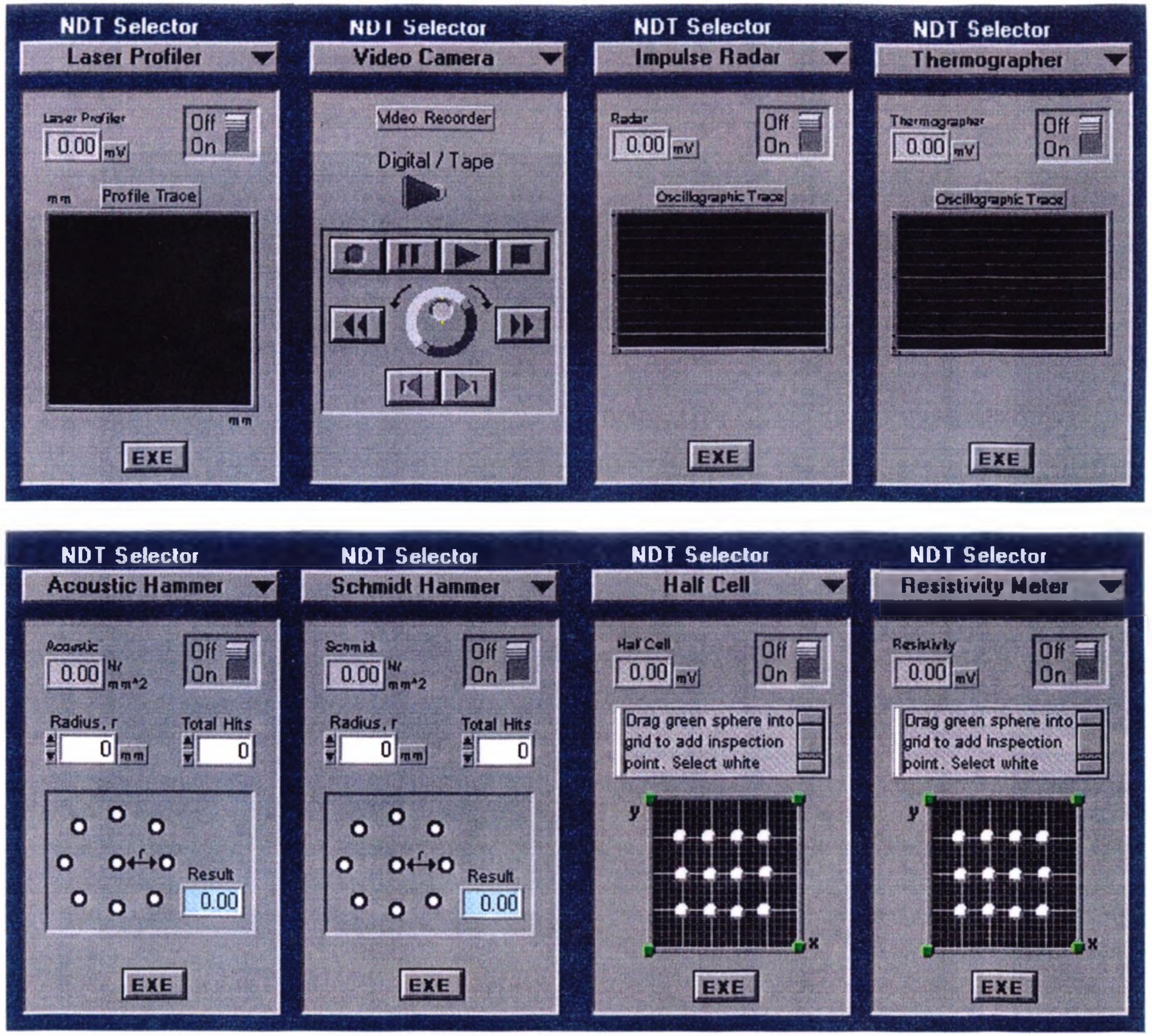


Figure 11.16 Right mouse clicking on the X-Y motion icon to bring up a graphical menu



Colour Plate 1: Main CURIO HMI Control Panel



Colour Plate 2: Other NDT Device Panels

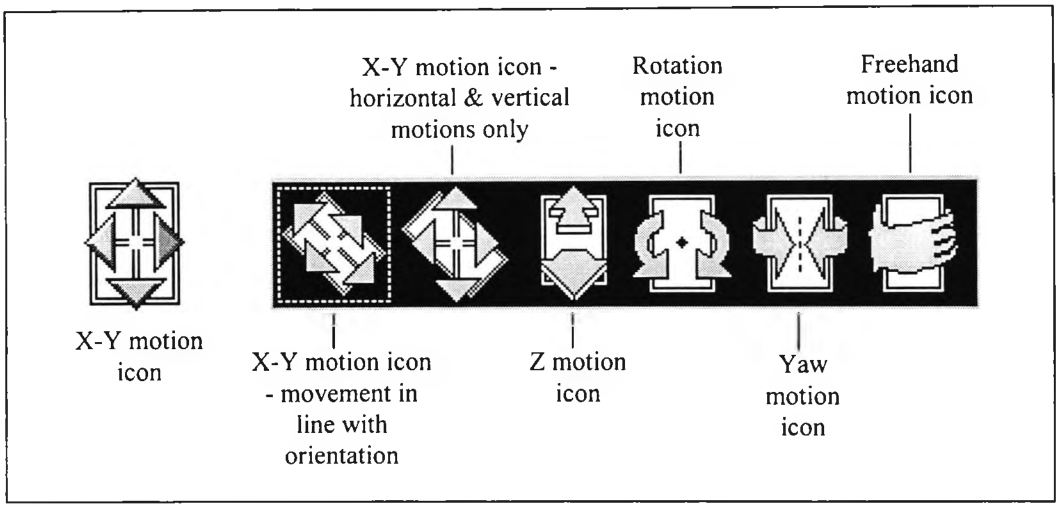


Figure 11.17 Actual size of the X-Y motion control icon and descriptions on its possible replacement

In the event an operator would like to perform a Z or Rotation motion, while having the original X and Y motion controls available, the operator may select the toolbar icon as depicted in Figure 11.18. The selection will bring up a floating panel with the afore mentioned motion controls, as depicted on the right of the figure.

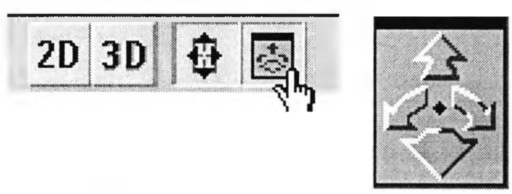


Figure 11.18 Bringing up the Z and Rotation motion control panel

11.4.2.2.2 Overall Screen Layout Design

The design of the HMI is divided into three main areas of operation, which are depicted alphabetically in Figure 11.13. Their discussion, however, are provided under four headings:

1. CURIO panel
2. NDT device panel
3. Workspace and
4. Toolbar

Before detailed discussions are given to these individual areas, the overall screen layout design is discussed next.

The screen layout design of the CURIO HMI is based on the observations of Chapter 7. As an aid to memorizing the principles, the author proposed the word 'PRACtical' as in 'practical screen layout design principles' to stand for proximity, repetition, alignment and contrast. These are discussed in turn with respect to the overall HMI layout design.

The 'proximity' of display elements define their perceived grouping and are used in organizing HMI elements. Referring back to the previous section, the design of the CURIO HMI consists of three main groups. The first group holds the controls for the robot, the second group, holds the NDT devices, and the third, the Workspace (Figure 11.13). As the design is based on a 'physical' control panel metaphor, these groups are designed to appear within panels.

The Workspace, which represents the test site, is the most important area in the HMI. Operators would perform an inspection within this, and it is also where the results from NDT inspections are placed. To attract the operator's attention to this area, the author has designed its panel to appear raised. The placement of the Workspace in the center of the HMI also assists in attracting an operator's focus. To keep the operator from being distracted by the neighboring CURIO and NDT device panels during an inspection, the author has designed them recessed. The CURIO and NDT device panels are placed on either side of the Workspace so that their respective controls are within close viewing distance from the latter.

'Repetition' is used to unify and add interest to a screen display. With the CURIO control panel, visual repetition of the 'CURIO' and 'NDT Selector' labels above their correspondingly, similar sized panels, create a sense of balance in the display. This in turn forms a feeling of stability and confidence in the operator. The visual repetition of the two panels also draws the operator's attention to the other, creating a sense of continuity in the HMI.

The main CURIO software 'alignments' are depicted in Figure 11.14 (indicated by dashed lines). The alignments are used to provide a visual connection between the different groups, and it gives the HMI an organized interface. Alignment is also used here, to unify the icons in the toolbar to their respective panels. All icons above a panel consist of functions, for the panel below it.

Colour is used to create a strong 'contrast' between the three main panels (foreground) and the background (see Section 1.3.1). The 'cool' dark blue background colour causes the background to recede, while the light gray colour of the panels standout at the observer. Contrast is used in this instance to attract the operator to the most important parts of the screen, the three panels. The larger size of the Workspace in comparison to the CURIO and NDT device panels, also attracts the operator's attention to the former.

11.4.2.2.3 CURIO Panel

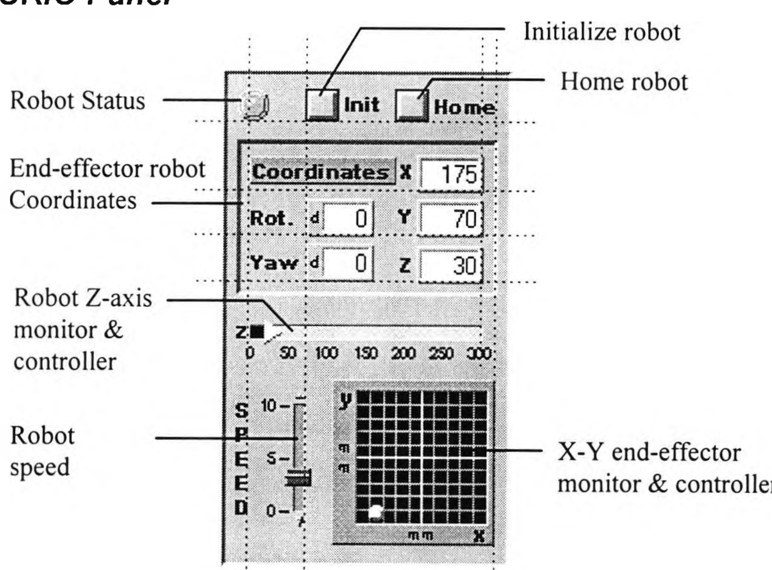


Figure 11.19 The CURIO panel. Dashed lines depict alignments of screen elements

The panel depicted in Figure 11.19 is used as a control and feedback panel for the CURIO robot. The layout of each element, is based on how each is used in the inspection process. Their alignment is depicted with dashed lines. To keep an operator's attention, close to the centrally located Workspace, the author has placed the most important and frequently used elements on the right. Starting from the top of the panel, these include the Home button, the X, Y and Z display coordinates and the X-Y end-effector monitor, while the less important elements are placed on the left side of the panel.

Colour is used in moderation, in the whole design of this HMI. In the CURIO panel, three colours are used; green, red and yellow. The rest are in shades of gray. With the robot LED status display, green is used to indicate normal, while a flashing red is used when the robot malfunctions, or stops responding (see Colour Plate 1). Flashing red is used because it easily catches an operator's visual attention. A warning siren also accompanies this flashing, so as to ensure the operator is informed of the critical situation.

As the sphere representing the X-Y robot end-effector position is small, the author enhances its visibility by making it yellow on a black background (see Colour Coding Tips of Chapter 4). To remain consistent, the triangle on the horizontal slider (Z-axis) is coloured yellow, as it also represents the robot's end-effector. Another reason why the colour was chosen is because, yellow is a warm colour. Warm colours draw attention, and is often used to indicate required actions (see Colour Coding Tips of Chapter 4). The latter point is used in the HMI to indicate that the X-Y, and Z end-effector monitors are themselves controls to their respective motions. To move in the X-Y plane for example, the operator would first select the yellow sphere, and then point to a new position within the gird. The robot end-effector will then take the shortest route to the new position.

11.4.2.2.4 NDT Device Panels

Depending on the quantity of objects to be displayed and their relationships to one another, an application may require numerous screens, or screen areas to depict them. With the former, users move from one screen to another to reach new material or objects; while with the latter, new material are brought into a fixed area of the current screen. Based on the point that only the NDT device in use is to be displayed and the permanency of the rest of the HMI elements (Section 11.4.1), the author employs the latter method in the design of the CURIO HMI. This is depicted as Area 2 in Figure 11.14. To move between the different NDT device panels, the operator has to first select the 'NDT Selector' button above the panel. A menu listing the options will pop-up, on the button, providing the operator with the option to select any one. When a selection is made, the appropriate NDT device panel appears in place of the former. The navigational style employs a single tiered hierarchical structure, similar to pull down menus found in most applications.

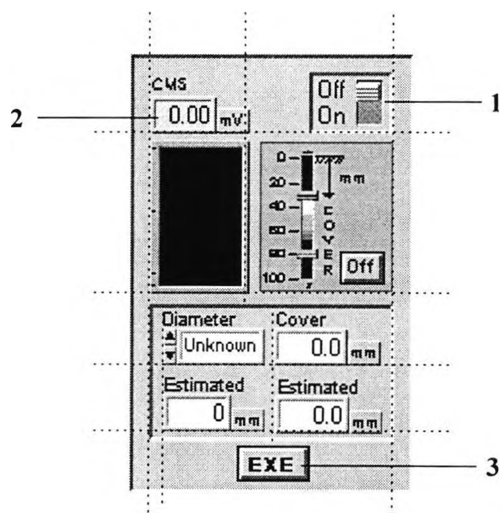


Figure 11.20 Covermeter NDT device panel. Dashed lines depict alignments of screen elements

Again, to keep the operator's attention close to the Workspace, the author has placed the most important and frequently used elements, this time on the left of the NDT device panels (Figure 11.20 & Colour Plate 2). The elements displayed on each panel are based on Table 11.2, and on how each device can be automated with the CURIO robot. The layout design of each panel, is based on creating a consistent HMI. For instance, the three numbered elements of Figure 11.20 are repeated, where appropriate, on some of the other NDT device panels, as illustrated in Figure Colour Plate 2. These consistencies, have the effect of speeding up an operator's training time, and later, execution time; based on the positional memory of each of these elements.

Four colours are used; red, green, a very light yellow, and a light cyan (see colour Plate 1). The green, however, appears in the last two panels of Colour Plate 2, while the red only appears on the covermeter NDT device panel. For the latter, a slider control panel is used to govern how depth-of-cover is depicted on the Workspace. This panel has two sliders, one dictates the maximum depth-of-cover level (values greater than this appear in black), while the other dictates the minimum level (values less than this appear in red). In between these levels, depth-of-cover values are displayed in gray scales. The colour red is used here, to inform users of low depth-of-cover readings. Within these NDT device panels, the author uses light yellow to depict input panels, while light cyan is used for output panels that show final test results. These colours were chosen because they provide good contrast between the display panels, and their gray background. Their use is also consistent, between all the different NDT device panels, making it easier for operator's to locate them quickly.

11.4.2.2.5 Workspace Panel

The Workspace panel (Figure 11.22), is where the video image mounted on CURIO is displayed, the test site surface profile from the laser profiler is viewed, and all other NDT test results are placed. The former two will be discussed in the next section. One of the greatest benefit of the Workspace is the ability to attain various NDT test results and to make comparisons between them. This recognizes that studies have shown that some combinations of NDT methods produce results which are much better than can be obtained from any of the methods individually (Facaoaru, 1969).

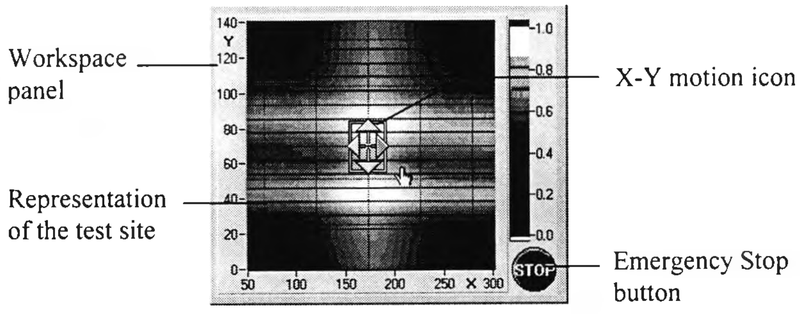


Figure 11.22 Workspace panel

In the middle of the Workspace, is the X-Y motion icon discussed in Section 11.4.3.1. On the bottom right, is a large red emergency stop button for the robot. The colour red reinforces the meaning of the stop sign. In a survey on the association of colour and meaning (Chapter 4), red had a 100% association with the meaning stop.

11.4.2.2.6 Toolbar

The first four icons above the CURIO control panel are for bringing up CURIO motion controls. These were discussed in Section 11.4.3.1. This section concentrates on the toolbar above the Workspace panel (Figure 11.22).

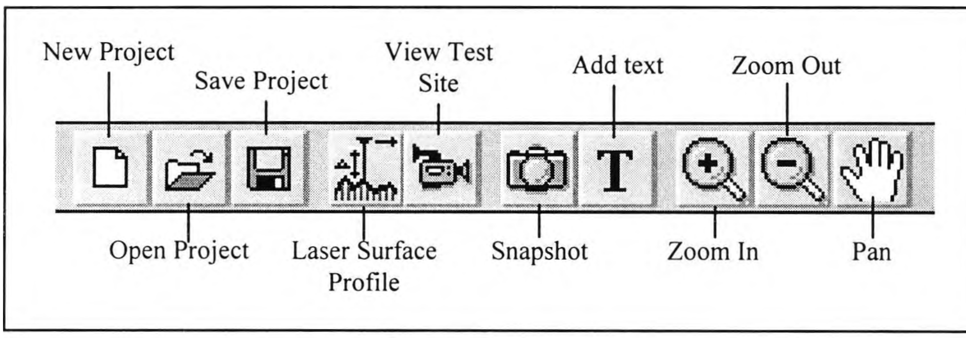


Figure 11.22 The toolbar

The first three icons in Figure 11.22, are consistent with Microsoft's standard. The first represents creating a new file, or in this instance, project. The second represents open an existing project, and the third is to save it. In this software, a project consists of all work performed on any single inspection site.

To reduce chances of collisions during an inspection task, a survey of the test site is recommended before performing the various NDT inspections. The next two icons in Figure 11.22, allows an operator to conduct such a survey. The first is automated, and is used by the robot in avoiding collision. For this, a laser profiler is used in a scanning process, across the whole surface area of the inspection site. The data collected is then used to build a topographical map, that is displayable on the Workspace. This map provides operators with a graphical representation of the test site. Most importantly, it is used by CURIO in programming the robot motion limits based on the surface contour of the inspection site; so that it may stay within safe working limits.

The next icon depicts a representational icon of a video camera. The video camera will be mounted on the robot's Z-axis, and can be is used for conducting a visual survey of the inspection site. The process, however, is performed manually by an operator. The video output is displayed on the Workspace, providing operators with live pictures of the structure they are working on. For tele-operations, this feature is essential to promoting a sense of working on a test site. The operator can also call up the previously obtained topographical map onto the existing video image by selecting the laser surface scan icon. If a contour map already exists, it is displayed, otherwise the robot will perform the necessary scan to obtain it. As the two icons are used in performing the survey, they have been grouped together.

The next two icons are for taking a snapshot of the Workspace, and for inserting any textual notes on the information displayed in the Workspace. The snapshot saves any images that is displayed on the Workspace. It uses a representational icon of a camera to depict this. The other icon uses the common 'T' to represent insert text. When a user selects this, the mouse cursor changes to an 'I-beam'. An operator would then mouse click on the Workspace to insert any textual information, he or she might like to add. Taking a snapshot of the Workspace also saves any textual information that was inserted.

The last three icons in Figure 11.22, are commonly found in graphical applications. To maintain consistency with their usage, the author also employs them here to represent 'zoom in', 'zoom out,' and 'pan.' This is with respect to the Workspace area.

11.4.2.3 Feel

The 'feel' of an application is determined by the interactive methods, style, and I/O devices employed by an application. The CURIO software, being in its early prototype, employs a monitor, keyboard, and mouse. Being mainly a mouse driven application, the software utilizes a direct-manipulation approach to interaction. To make this more apparent at the interface, the HMI employs an interface with a familiar 'like real' control panel; with switches, slider-bars, buttons, LED displays and knobs. With the latest HMI design, where the CURIO control panel is embedded in the middle of the Workspace, the author has managed to create a more direct 'feel' to inspection.

Based on the control panel design of the latest CURIO HMI software, and the input device task suitability table of Chapter 7 (Table 7.1); the author proposes, researching the replacement of the mouse input device with a touch screen. Even though joysticks are commonly used in driving construction robots (HMI Questionnaire Survey, Appendix G), the author finds that with the latest CURIO software prototype, the need to drive CURIO is often superseded by inspection processes that can often be automated. The benefits of using a touch screen include low cost, robustness and their provision for a more direct, and natural form of input.

As the system is to be implemented outdoors, the touch screen would have to be coated with an anti glare film. To counteract the disadvantage of arm fatigue, which is often associated with using a touch screen; the author recommends housing it at an angle of about 30° to the horizontal. The incorporation of armrests around the screen should also provide for greater operator comfort.

Other I/O devices such as a dataglove, head mounted display and a voice recognition system could further extend the directness felt in the interaction of the CURIO system. Development cost, and the time frame in which to build such a system, however, would probably take too long for this project. Furthermore, such systems would currently not be commercially viable.

11.4.3 A Typical Covermeter Inspection Sequence

Figure 11.23 is used to describe this inspection process. Assuming the robot is at the inspection site, and ready for inspection. To re-initialize the CURIO robot, the operator selects the 'Init' button. The initialization performs an internal diagnostic that verifies the functionality of the robot and its system. The robot is also 'Homed' automatically [2] when this is performed. 'Homing' the robot sends its end-effector to (0, 0, 0, 0). To begin a new project, the operator selects the icon marked 8.

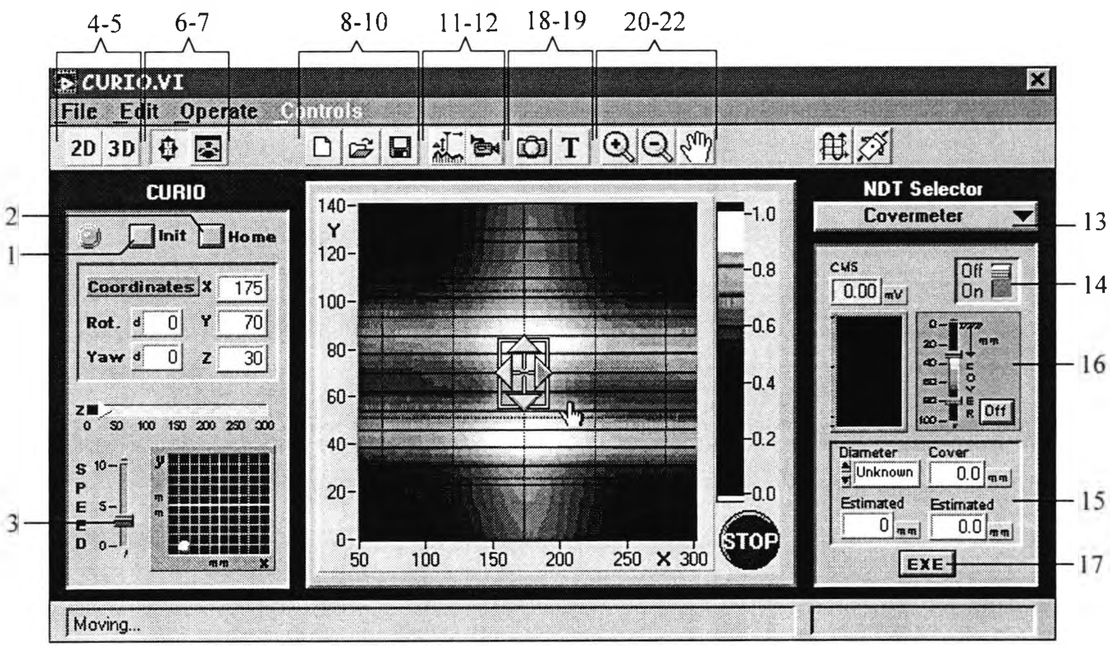


Figure 11.23 CURIO software

Before performing an inspection, the operator would conduct a survey of the inspection site by selecting the icon marked [11]. The robot then conducts a laser profiler scan of the whole site, to obtain its surface configuration. This information is used by the robot in setting it's own motion limits, so as to prevent any collisions during a manual or automated inspection process. A topographical map of the surface is also displayed on the Workspace, providing operators with a visual representation of the site. A snapshot of this can be taken by selecting icon [18], which is saved with the project. The operator can then perform a live video survey of the inspection site by selecting icon [12]. The captured video images are displayed on the Workspace. This inspection process is tele-operated, and the operator performs this with the aid of the X-Y motion icon in the middle of the Workspace. To manipulate the Z and rotation motions of the robot, while still having the X and Y icon controls available, the operator would select icon [7], to bring up a floating panel as depicted in Figure 11.18. The Z-axis motion will enable closer examination of the site. To enable recording of this visual inspection, the operator may use the recording controls in the Video Camera NDT panel. This panel would be displayed when the operator selected icon [12]. To save a still image, the operator would use the snapshot camera icon [18].

To perform a covermeter inspection, the operator would first bring up the covermeter panel by selecting the appropriate selection from the menu bar [13], which brings up the panel as depicted in Figure 11.23. To begin inspection, the operator would turn on the covermeter instrument, using the switch marked [14]. This also stores the value of residual in-air signal for subsequent correction to all measurements. The operator would then enter the known size of the re-bar to be detected, if the value is known in advance, otherwise it is left indicating unknown. The operator would then select the Execute button [17] to begin the automatic covermeter inspection.

The automatic inspection process, described in point format below, is then performed. The result of each step is displayed on the Workspace, providing feedback to what is being performed. The steps follow:

1. A horizontal and vertical scan is performed on the structure to determine the orientation of the re-bars with the closest depth-of-cover.
2. A thorough (horizontal or vertical) surface scan is performed to locate the position of the re-bars with the smaller depth-of-cover values, determined in Step 1.
3. A surface scan is then performed between the located re-bars of Step 2. In this scan, re-bar size and depth-of-cover estimations are performed on each location of a re-bar. Each of these estimations is displayed in panel [15].
4. A surface scan is then performed to estimate the re-bar sizes and depth-of-covers of the first located re-bars, determined in Step 2; this time, however, in between the re-bars located in Step 3.

5. The image in the Workspace currently displays raw covermeter signal readings. To obtain a true representation of the located re-bars and depth-of-cover, the operator would set the sliders on panel [16], and turn on the image processing option. This action links the located re-bars to form continuous, vertical or horizontal representations of them. The raw covermeter signal readings are also reduced to the estimated re-bar sizes, and shaded to correspond to the settings, on panel [16]. The final image is then saved as a snapshot. An example of this is provided in Figure 11.24. In this case, depth-of-covers of all re-bars forming the grid, decreases from left to right.

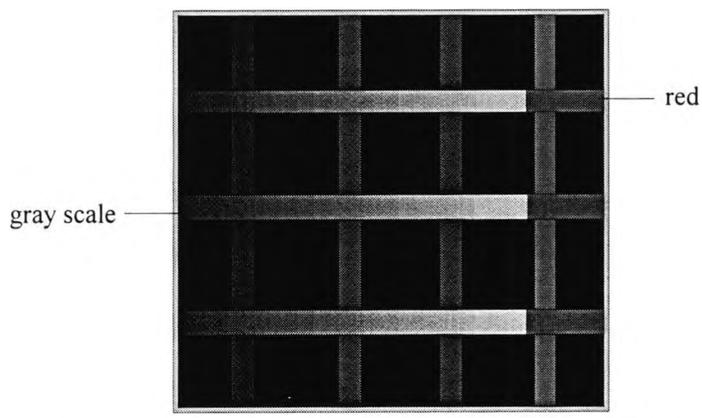


Figure 11.24 Post processing samples of raw signal data

To conduct detailed and more complex inspections, as in the lapping re-bar case of Section 10.6, the operator can intervene, using the X-Y motion icon.

11.5 Conclusion

Three phases were performed to reach the proposed software prototype for CURIO, and three different motion control panels were designed in the process. The first two control panel designs are essentially the same, as they were specifically designed to control the robot. The first design uses a conventional 2-D approach to the placement of the motion buttons (Figure 11.15), while the latter uses a 3-D perspective approach (Figure 11.15). The third design, however, makes the control of the robot less like controlling the robot, than controlling an inspection process. In this latest design, the controls have been reduced down to those frequently used during an inspection, i.e., X and Y motions. Instead of thinking about the various positions of the robot end-effector, and how they may be controlled, the operator is better able to focus on the design process with this latest design. Being simpler to use, this design (Figure 11.14), provides operators with a more direct and focused approach to inspection.

Based on the study of the NDT devices (Table 11.2 & Appendix C) to be incorporated on the robot, all inspection processes show potential of being automated to some degree. A typical covermeter inspection process, covered in the last section (Section 11.4.3), provides detailed discussion of how this can be achieved. Colour Plate 2 depicts the panels of the other NDT devices. Their designs also show their potential for automation.

Combining NDT inspection methods have been shown to produce results, which are better than any single method (Facaoaru, 1969). One of the greatest research potentials of this project, is the ability to easily compare different NDT inspection results. With a working CURIO model, new ways of combining different NDT methods can be studied easily.

The whole design of the latest HMI is based on the chapters covered in Part 1 of this thesis. Unfortunately, as the CURIO robot is unavailable for formal testing of the HMI, there are no formal test results on the software meeting the intended HMI objectives of this project. However, from informal tests that were conducted on the HMI (Appendix H), candidates have shown their preference for the latter HMI design.

12. Conclusions

There are two main objectives to the research; the development of a 'user friendly' HMI command center for the remote control of the CURIO robot, and the computerization of various NDT devices. The latter has been worked out in detail for a re-bar covermeter.

12.1 Main Conclusions

Pertaining to the original objectives of Section 1.6, it is now possible to evaluate to what extent each goal has been met. Part 1 of this thesis achieves the first two goals of the research. The first goal was to research the factors that influenced the effectiveness of the HMI provisions, and to produce guidelines for their implementation. The second goal was to investigate input and output devices, their influence on HMI design, and their task suitability. Conclusions are provided in each chapter, but are here summarized as follows:

1. HMI psychology forms the foundation upon which most of the guidelines in the thesis are built. The author has identified six fundamental principles in the areas of perceptual grouping, depth perception, context, human attention, human working memory, and finally, control. These are described further in Chapter 2.
2. Forming the right mental model for a user, is essential to developing an intuitive HMI. A designer achieves this through developing a conceptual model which reflects the corresponding mental model. The conceptual model of a designer is made of three components; 'object relationships,' 'feel,' and 'look.' The former is generally reflected at the interface, through the use of a metaphor (or metaphors) and through the employment of an intuitive navigational system. The former usually provides users with an overall functional understanding of an application, while the latter informs users specifically how the individual elements are organized in different screens or screen areas. Chapter 3 provides extensive examples of each.

3. Chapter 4 discusses the next area of the conceptual model, the 'feel' of an application, which is influenced by the input and output devices used in interacting with the HMI, and hence its design. The chapter provides detailed studies of existing, and developing devices for the future. To assist designers in the first stage of selecting an input device for a HMI, a task suitability table was created for the input devices covered in the chapter.
4. The following three chapters (Chapters 5, 6 and 7), research the 'look' of an application, starting with the chapter on colour, then on icons, and finally, on screen layout design. Colour can be used in four ways in HMI design; to identify, to inform, to please, and to depict. There are also four considerations to take into account when designing with colour; physiology, perceptual psychology, expectation, and preferences. Based on these considerations, Chapter 5 provides 50 guidelines on colour design.
5. The design of graphical elements in a HMI can generally fall into three categories; representational, symbolic, and sign icons. In designing such graphical elements, it is best to design them in the represented order of preference, as the abstractness of a design increases when moving from a representational icon to a sign icon. To assist designers in selecting the best graphical representation for an icon, Chapter 6 proposes a contextual object selection methodology. To further enhance iconic understanding, such techniques as the use of context sensitive help, animation, and sound (earcons) to communicate functionality, properties and actions were proposed.
6. Chapter 7 researches the area of HMI screen layout design. It is found that research contributions relating to guidelines are increasing in number, to an extent that their implementation in a HMI design process is proving difficult. Most of these are in the written form, which mean that they are difficult to access, and interpret. Research in incorporating such guidelines into a knowledge-based critiquing system is promising, but such systems are yet to be released commercially. To counteract the limitations of current written guidelines, the author proposes four design principles on layout design, that encompass most of the guidelines in a generalistic manner. The author's design principles are

embedded in the first four characters of the word 'PRACtical,' as in 'practical' screen layout design principles. 'PRAC' stands for proximity, repetition, alignment, and contrast. Chapter 7 provides detailed examples for each.

The third goal of investigating a method for automating a covermeter with a robot is addressed in Chapter 9. Four existing techniques were looked into. Whilst three of these were found suitable for automation with a robot, a new method is proposed because of its greater potential and suitability to the task. The new method is based on analyzing a traverse profile for estimating re-bar size, and hence, depth-of-cover. This method, unlike the other four methods, employs a scanning operation to determine the two unknowns. The other four methods rely on performing spot readings directly on the re-bars to be determined. Their operation times are, therefore, much slower in comparison to the new so called 'Traverse Profile Width Method.' Such operations are conducted in two stages, while the latter is performed in a single pass. With the latter, the first stage involves determining re-bar positions, while the second stage involves performing spot readings on all the re-bars to be determined. Two out of three of the proposed automation methods are also iteratively intensive, thereby slowing the operation considerably.

As the covermeter is employed in conjunction with a robot, the spatial position of a detected re-bar can be determined in three dimensional space (x, y, c). The accuracy of the x and y positional coordinates are theoretically of the order of one hundredth of a mm, with the CROCUS robot. With the new Traverse Profile Width Method, depth-of-cover (c) estimations, fall within the standard set by BS1881:Part204, i.e., to within ± 2mm or ± 5% actual depth-of-cover. Re-bar size estimations of this method also meets the standard, i.e., to ± 1 regular re-bar size (see Table 10.3 or Appendix F-3). Therefore, the accuracy of the new method, fulfills the forth and fifth goals of the research.

The sixth goal is also accomplished with the new method, as it can be performed in a much shorter time than a manual inspection employing one of the four existing methods, discussed earlier. As the process is automated with a robot, the inspection can also be performed more thoroughly and reliably. An example of a typical covermeter inspection process employing this new method is discussed in Section 11.4.3.

The seventh goal of the research was accomplished in Part 3 of this thesis, by integrating the developments in Part 1 and Part 2 in building an application for the CROCUS and CURIO robots. To achieve the eighth goal of a more transparent, and intuitive HMI for the robot control panel, the author integrated the operation of the robot and the inspection process, into a single operation. In doing so, the design promotes a more direct approach to inspection (see Section 11.4.2.2.5). Validation and assessment of the effectiveness of the various proposed HMI designs for the CURIO robot are discussed in Appendix H. This however, was conducted informally, as the CURIO robot was unavailable for formal testing of the CURIO software.

To promote confidence and hence encourage exploration of the system, the author proposes a method of reducing chances for collision. To achieve this, a laser profiler is first used to scan the surface to be inspected. The result of the scan provides knowledge of the terrain of the inspection site. This information would be used by the robot system in delivering collision free motion, thus satisfying the ninth goal. In the research, the author observed that most of the proposed NDT inspection processes of Appendix C could be automated successfully, to a considerable degree. In the case of automation, the requirement for instantaneous feedback is less crucial than in the case of tele-operation. Therefore, such time factor complications as transmission delays, often encountered with such systems, are less significant. The integration of these inspection processes into the CURIO HMI (see Section 11.4.2.2.4) is discussed in Chapter 9, thus fulfilling the final goal.

12.2 Future Developments

It is unfortunate that the hardware developments of the CURIO robot system, have not been in line with the developments of its HMI and NDT related software. A considerable amount of integration work is still necessary. The research, however, lays the groundwork for these to be performed in the future. Additional investigations in such areas as transmission delays, incomplete feedback and unanticipated interference are anticipated. This thesis has not looked into these areas as they are often very specific to the design of the system. Ways of correcting, or reducing their effect on tele-operations, through HMI designs, can be performed when they have been identified.

The automation of the covermeter with the CROCUS robot represent a blue print for the automation of the other proposed NDT devices. These latter devices are easier to automate, as their processes are straight forward in comparison to the covermeter. Such developments, however, are not within the time scope of this thesis, and would form work to be accomplished in the future.

Appendix A

The CURIO Project

A.1 Introduction

This appendix reviews the CURIO (City University Remote Inspection Operations) project at City University (Chamberlain et al., 1994). A brief account is given of each individual project that contributes to the research program. This chapter gives an explanation of where the author's research fits into the overall picture of the CURIO project.

A.2 The CURIO Project

The emergence of research in automation in the Construction Industry, particularly in the area of inspection, can be attributed to various factors. Repair and maintenance requirements in the UK are estimated to cost approximately £16 billion per annum (Cusack & Thomas, 1992). From this, an estimated £15 to £18 million per annum is spent on inspection. Clearly, the market for inspection is substantial. A feasibility study undertaken for the UK Department of Trade and Industry (DTI) by CIRIA in 1986-87 identified the area of inspection as having the greatest potential for automation and robotics in the construction industry.

Inspection automation using robots would also eliminate risk to human life. Safety statistics for the construction industry, from 1981 to 1985 showed that maintenance activity accounted for between 34% and 50% of fatal accidents (Cusack & Thomas, 1992). Half of this percentage is due to falls from scaffoldings and ladders. Other favorable factors for automation include greater quality assurance, reliability of survey data, automatic data logging with positional readings, and computer based post-processing of logged data.

The Construction Robotics Unit was founded in 1990 as part of the Structures Research Center of the Civil Engineering Department. The main aim of the center is to research automation and robotics in the Construction Industry. There are currently six individual projects underway at the Construction Robotics Center, of which five contribute directly to the CURIO project, the other is a masonry wall building robot. CURIO however, is under development to meet the requirements of the inspection, maintenance and repair (IMR) of buildings and structures, which represents a major part of the construction industry's activity, worldwide.

Figure A.1 gives a graphical representation of the CURIO project showing how the individual projects contribute to the project as a whole. The left hand side of the figure lists the people involved in this project. Next, is a floppy disk which represents the software development requirements of the project and on the far right, within the rectangular boundary of 'Hardware', lies the hardware specification of the project.

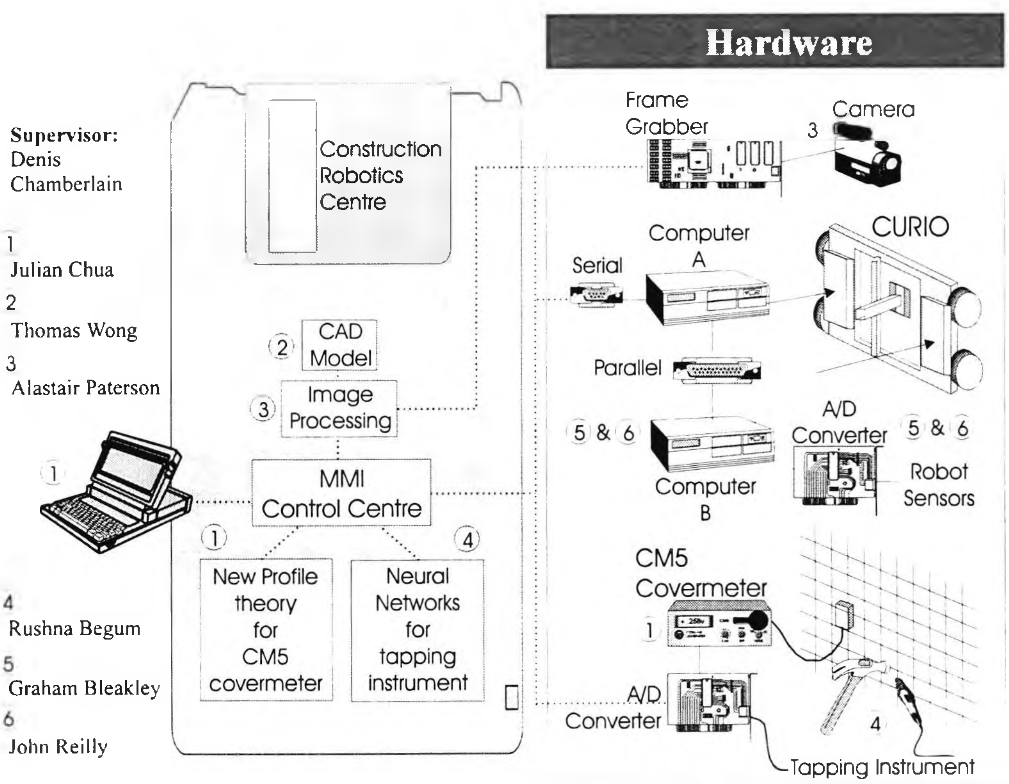


Figure A.1 Graphical overview of the CURIO project

A.2.1 Human-Machine Interface (HMI) and NDT Automation

The author's research concerns the HMI command center for the remote control of CURIO. Factors that influence the effectiveness of the HMI provisions for robot operators are investigated, and guidelines for its development worked out. The research also includes the automation or computerization of non-destructive testing (NDT) equipment to be employed by CURIO and a proposal is given on how these would interface with the HMI command center. A simple software/hardware graphical representation of the authors work is provided in Figure A.1, labeled with the numeral 1.

Much of the author's research has also gone into the automation and computerization of a CM5 CoverMaster covermeter, which employs a new traverse profile theory. Details of this new traverse profile theory and all the empirical experiments that have gone into its development, are given in Chapter 10.

A.2.2 CAD Modeling of Buildings

T. Wong's main area of research is to develop a design philosophy for CURIO based on an integrated approach towards current inspection methods, availability of current technology and tall building features. Analysis is being made of the common features of tall buildings, and CAD models are being prepared. These CAD models will be used in conjunction with the visual navigation system, as explained in section A.2.3. A design of a universal suspension track for CURIO to suit tall buildings with common features, is proposed. The software representation of this research, with respect to the others, is provided in Figure A.1, labeled with the numeral 2.

A.2.3 Visual Navigation System

In order for CURIO to be deemed practical as an inspection robot, it is necessary to know its location on a work site so that defects can be accurately recorded. The working surface envelop of CURIO provides local positioning with respect to itself. To provide for a more global positioning facility, work on image processing has been done by A. Paterson to locate CURIO on building sites. The technique uses a single uncalibrated video camera which is placed in a position where it can view the building. This is connected to a ground computer or HMI command center via a low cost frame grabber card.

Three stages are identified in determining the global position of CURIO (Paterson, 1995). The first is an image capture of the robot on the building site. This is processed in the next stage which uses a CAD model of the building under test to obtain a coarse positioning of the robot with respect to the building. The final stage uses the video camera on CURIO, which is also used for visual inspection and which has been pre-calibrated to measure its orientation to a specific feature on the current test area to obtain a finer positioning. The advantages of employing this technique include, not having to calibrate the camera, placement of camera does not have to be accurate, no measurements are required and no complex stereo vision or photogrammetry need be performed (Paterson, 1996). The software/hardware graphical representation of Paterson's research is provided in Figure A.1, labeled with the numeral 3.

A.2.4 Neural Network Impact Echo Testing

The impact-echo method is one of the NDT methods that is being investigated for the inclusion in the CURIO project. This area of research is being carried out by R. Begum, who is employing Neural Networks in the interpretation of the output of the impact-echo system. Interpretation is based on the frequency analysis of the surface displacement wave form. ANSYS, a Finite Element Analysis (FEA) program from ANSYS, Inc. (USA) is being used to model concrete defects from which the results are to be compared to practical results. The results from both theoretical and practical experiments are analyzed using Artificial Neural Networks for classifying defects at varying depths. The impact-echo equipment comprises an impact device, a surface displacement transducer and an echo signal analyzer (refer to section D.5 for further information).

A.2.5 Vibration Elimination, Safety and Risk Assessments for CURIO

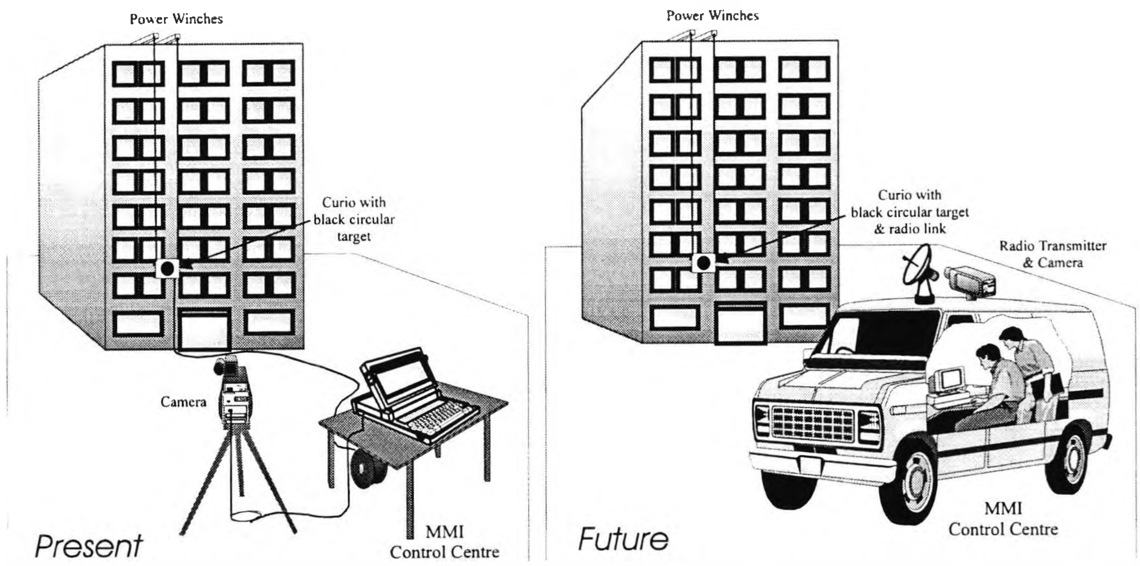
G. Bleakley's research objective is the elimination of the effects of vibration on CURIO. Transient and non-linear control algorithms are being investigated as the means of combating disruptive vibration. In addition, a Safety and Risk Assessments on the internal control systems of the robot is being performed, using rule sets and uncertainty factors which lead on to computer simulation of the controls with the derivation of failure probabilities. Part of the research also includes the development of CURIO itself. Further information on CURIO is provided in Appendix B. The hardware representation of this research with respect to the others is provided in Figure A.1, labeled with the numeral 5.

A.2.6 CURIO Development

J. Reilly is largely responsible for the electronics of CURIO, including robot sensors. The hardware representation of this research is provided in Figure A.1, labeled with the numeral 6. As the processing demands of CURIO are high, a distributed processing solution has been adopted. It uses two in-built 486s with parallel link communications and an external portable notebook computer on the ground to provide the man-machine control interface. The two 486s on the robot are individually assigned as having command interpretation, path planning and sensor feedback on one computer and motor control on the other as their main function. Communication between the robot and the ground computer is via an RS232 cable link which will be superseded by a radio link at a later stage.

A.3 CURIO Inspection Setup - Present and Future

The general layout of the present setup for a typical inspection process is shown in Figure A.2(a), and future projections with radio links in Figure A.2(b). The latter has the advantages of being in an inconspicuous environment; therefore attracting less attention, easy mobility, quiet working environment, which provides better audible feedback on any processes that may be running, better working conditions and finally placement of video camera that is less likely to be obstructed. With future research into incorporating voice commands on CURIO, the enclosed environment of Figure A.2(b) would also provide for better voice recognition as there would be less noise within the enclosed area.



(a) Present setup (b) Future setup

Figure A.2 CURIO inspection setup

Appendix B

CURIO & CROCUS Robot

B.1 Introduction

This appendix provides descriptions on both the CURIO and CROCUS robots used in the development of this project.

B.2 CURIO & CROCUS

CURIO stands for "City University Remote Inspection Operation" and was built to meet the market of IMR (Inspection, Maintenance and Repair). CURIO is a prototype man-machine system which uses roof level power winches to rapidly maneuver a robotic probe handling device over a building surface.

It is similar in many ways to the CROCUS robot used at the initial stages of the project. Both are 5 degree of freedom (DOF) robots, three prismatic axes and two revolute axes. At writing, CURIO has yet to have the two revolute axes mounted.

The CROCUS robot has a surface working envelope of 5.0m x 2.5m and CURIO has 1m x 1m. This surface working envelope represents the X and Y axes respectively. The CROCUS robot has a Z-axis with a reach of 2m while that for CURIO is 0.25m. The two revolute axes include rotation in the Z-axis and Yaw in the X-Y plane. Maximum velocities of 200mm/sec are achievable for the X and Y axes and 50mm/sec for the Z axis. The Rotational axis has a range of 315 degrees and the Yaw axis 102 degrees with both having expected speeds of 60 degrees/sec. Figure B.1 is a photograph of CURIO with the CM5 CoverMaster covermeter mounted on the control box on the right-hand-side (shown left in the photo) and its search probe in the grasp of the end-effector. A photograph of the CROCUS robot, performing a Traverse Profile Width Method experiment is provided in Appendix E, Figure E.1.

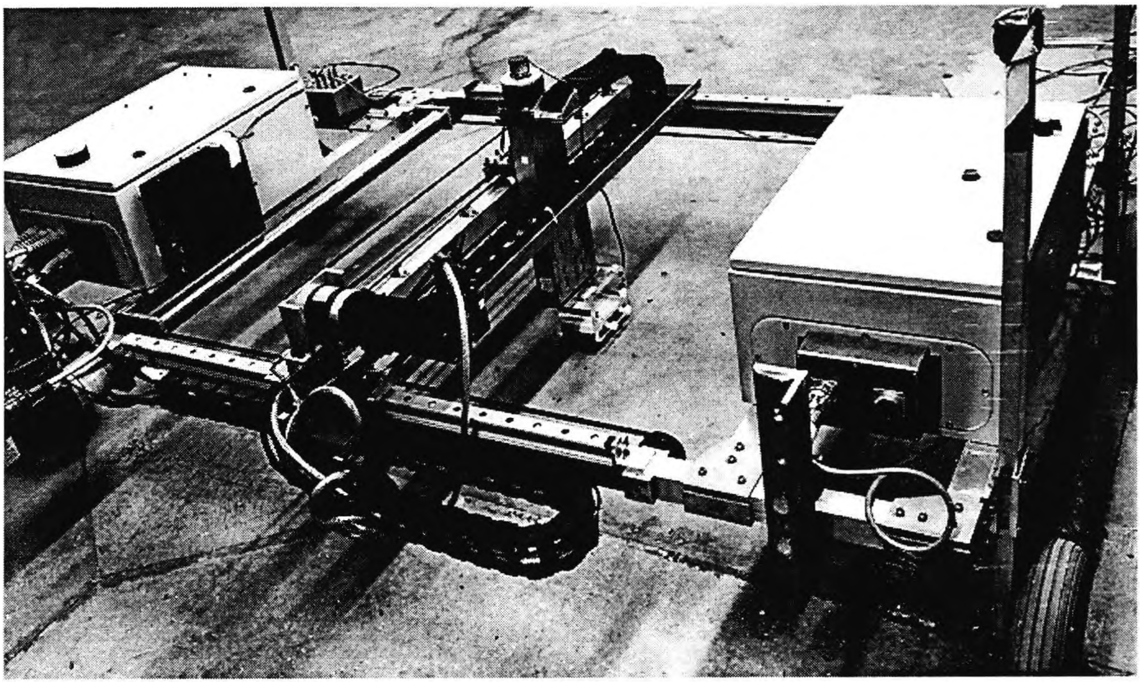
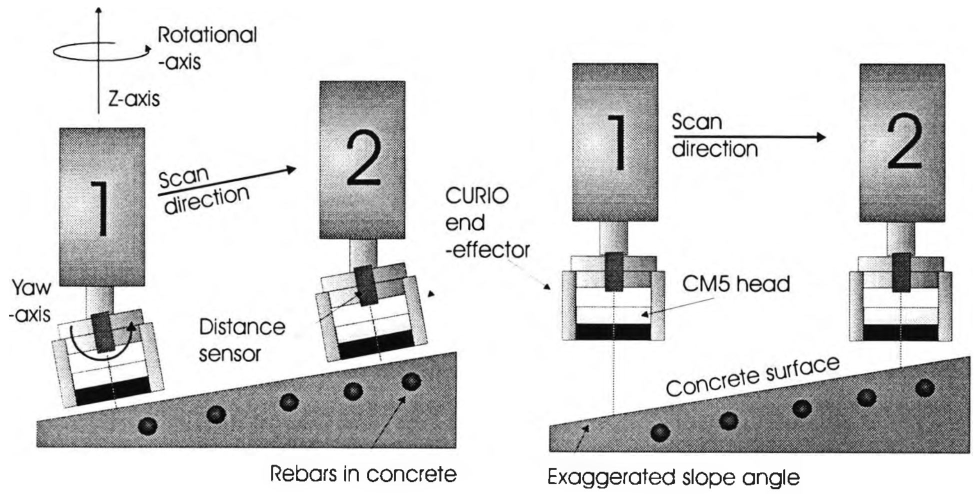


Figure B.1 CURIO with mounted CM5 covermeter

The rotational axis is obviously needed for situations where the bars to be measured are not exactly vertical and for any orthogonal measurements that may be required. The yaw-axis is used in conjunction with the other three prismatic axes (mainly X with Z or Y with Z) for scanning surfaces on an incline (Figure B.2(a)). The Z-axis is used to clear any obstacles and is also used on inclined surfaces by taking readings from a pre-defined distance from a single point on the concrete surface while using distance sensors (a laser range finder) on the robot end-effector or tool attachment point (TAP) to measure the actual distance from search head to the concrete surface during the scanning process in order to obtain true cover (Figure B.2(b)).

When performing a surface scan as in Figure B.2(b), the surface incline cannot be too large. Large distances would cause the covermeter to exceed the depth range of the CM5 covermeter, which is about 90mm. However, as the working envelope of CURIO is almost always in parallel to the concrete surface, large incline angles are rarely encountered. Even in these rare occasions, the scanning method as shown in Figure B.2(a) can be employed. Method B however, is employed most often as it is simpler to perform and requires less processing in terms of tracing the contours of an inspected surface. This contrasts well with the manual mode of operation where the CM5 head is always in contact with the concrete surface.



(a) Method A (b) Method B

Figure B.2 CURIO end-effector orientation for scanning surfaces on a slight incline

As the processing demands of CURIO are high, a distributed processing solution has been adopted. It uses two in-built 486s with parallel link communications and an external portable notebook computer on the ground to provide the man-machine control interface. The two 486s on the robot are individually assigned as having motor control or sensing as their main function. Communication between the robot and the ground computer is via an RS232 cable link which will be superseded by a radio link at a later stage. C language is used for the low-level hardware control of the robot and initially, G language from National Instruments LabView application was used for the programming of the man-machine interface of the ground computer but this has been recently replaced by a Windows application written entirely in the C language.

Appendix C

NDT Equipment for CURIO

C.1 Introduction

This chapter discusses the NDT equipment that are to be employed on CURIO and their feasibility for automation. The chapter begins with a discussion on the test equipment that are commonly used in structural inspection. A process of elimination is then carried out to determine which are suitable for automation and CURIO. Following this, a short brief is given to each of the NDT equipment selected and their features extracted for the process of automation and HMI.

C.2 NDT Selection for CURIO

The selection of testing equipment to be employed on CURIO will only be of the form of non-destructive methods. A major reason for this is because destructive equipment tends to be large and heavy in order for them to break through concrete structures. This makes them unsuitable for CURIO because of their high pay loads and heavy vibrational effects when employed. NDT equipment however, tends to be small and light, hence making them suitable for robotic application.

Before selections are made on the NDT equipment, it is first important to determine which of these devices are commonly used during inspection so as to be able to improve CURIO's employment during inspection. A survey on this was conducted by the Construction Robotics Center (Nayee, 1992). Table C.1 shows the summary result of the survey in terms of frequency of use of commonly employed testing equipment. The results of the survey are from studies of construction companies in the London area, these companies claim to be leaders in their field.

Table C.1 Frequency of use of each test method

	Methods	Total Opinion
1	Covermeter	91.65
2	Drill Samples	90.65
3	Acoustic Hammer	82.6
4	Coring Machine	72.15
5	Half Cell	72.05
6	Schmidt Hammer	63.1
7	Resistivity	57.05
8	Ultrasound	56.05
9	Impulse	41.05
10	Video Camera	34.06

Table C.2 sets out the automation factors for the various inspection testing methods (Chamberlain, 1994). The auto-factor in the table is based on an arbitrary scale from 0 to 1. This factor is a measure of the ease or difficulty with which automation of testing can proceed, 0 being easy to automate and 1 being very difficulty. The auto-factor scale in Table C.2 is dependent on various factors such as weight, vibration, accuracy required etc.

Based on the results of Table C.1 and Table C.2, a covermeter was chosen to be the first instrument to be employed on CURIO. The covermeter is an obvious choice because it is one of the most commonly used inspection devices and it also stands a good chance of being automated successfully. The covermeter auto-factor of 0.3 (Table C.2), is however being optimistic as the ability to measure depth of cover is based on the fact that the re-bar size has to be known in advance. However, progress has been made in this direction as demonstrated in Chapter 10.

Table C.2 Concrete Inspection & Testing Automation Factors

						Probe Operation Requirements							
Hardware	Inspection test element	Standards	Data collection	Material Sample	Probe support unit. wt. & power	Manipulation requirement P/L/A	Wt. inc. sensors & motors	Location accuracy required	Robust -ness of probe	Ops. Sensing requirement ex. location req.	Total probe power	Shock vibration incducing (0-1)	Total auto factor
Video Camera	Visual defects, dimensions, cracks etc.	N/A	Video recorder & frame store	N/A	Video Recorder. 5kg. 40Watts (Frame store: Direct)	Static, pan, zoom. (A)	2kg	Low	Medium	On Board	Small	N/A	0.1
Covermeter	Re-bar location & cover depth	BS 1881 Part 204	Analog (Direct)	N/A	Micro-processor with A/D board (Direct)	Close proximity parallel plane trans. & rotation (L/A)	2kg	High	High	Close proximity & parallel	Small	N/A	0.3
ring Machine	For strength & carbonation test samples	For BS 1881 part 6 test samples	N/A	Cores up to 150mm diameter	Coolant supply, location drives 25kg, 1kW	Normal to surface, contact, anchor, core exct. & plug (P)	120kg	High	High	Normal, contact force & depth	3kW	High vibration	0.8 (semi: 0.3)
Drill	Dust samples through depth	N/A	N/A	Separate d dust samples	Air, vacuum, dust collection unit & drives. 20kg. 0.5kW	Normal to surface, contact, anchor, dust bag & plug (P)	20kg	Medium	High	Normal, contact force & depth	1.2k W	High vibration	0.6
Half Cell	Re-bar corrosion	(ASTM) BS 1881 part 211	Analog (Direct)	N/A	Micro-processor with A/D board (Direct)	Contact with surface (P/L/A)	2kg	Medium	Low/ Medium	Contact force & approx. normal	Small	N/A	0.3
Acoustic Hammer	Render & cover delamination	N/A	Analog (Direct)	N/A	Micro-processor with DMA A/D board (Direct)	Two elements normal strike & contact (P)	12kg	Low	High	Contact force and normal	.2kW	Medium shock	0.2
Laser Profiler	Surface & edge damage	N/A	Analog (Direct)	N/A	Micro-processor with A/D board (Direct)	Parallel proximity to surface sweep (L/A)	2kg	Low	Medium / High	Proximity to surface or edge	Small	N/A norm. op.	0.2

Direct: implies use of common micro-processor collection and processing P = Point / L = Line / A = Area Weight & power values all approximate

Table C.2 Concrete Inspection & Testing Automation Factors (Continued)

						Probe Operation Requirements							
Hardware	Inspection test element	Standards	Data collection	Material Sample	Probe support unit. wt. & power	Manipulation requirement P/L/A	Wt. inc. sensors & motors	Location accuracy required	Robust -ness of probe	Ops. Sensing requirement ex. location req.	Total probe power	Shock vibration incducing (0-1)	Total auto factor
Impulse Radar	Re-bar location, delamination , voids etc.	N/A	Analog to special unit	N/A	Special Support unit. 50kg. 1kW	As for covermeter + speed control (L/A)	2kg	High	High	Close proximity & parallel	Small	N/A	0.3
Resistivity	Re-bar corrosion	N/A	Analog (Direct)	N/A	Micro-processor with A/D board (Direct)	Contact with surface (P/L/A)	2kg	Low	Medium	Normal & proximity	Small	N/A	0.3
TOF Ultra-Sound	Concrete strength	BS 1881 part 203	Analog (Direct)	N/A	Micro-processor with DMA A/D board (Direct)	Two element contact with jell seal (P)	2kg	Medium	Medium / high	Close flush fit & force	Small	N/A	0.6
Schmidt Hammer	Hardness	BS 1881 part 203	Analog (Direct)	N/A	Micro-processor with A/D board (Direct)	Contact normal with held reaction (P)	8kg	Low	High	Normal, contact & force	0.2k W	High shock	0.4

Direct: implies use of common micro-processor collection and processing P = Point / L = Line / A = Area Weight & power values all approximate

The other instruments that are to be employed, based on Table C.1 and Table C.2 include a video camera, half cell, acoustic hammer, laser profiler, radar, resistivity, Schmidt hammer and thermography. A discussion is given to each in what follows. The covermeter is covered in detail, in Chapter 8.

C.3 Video Camera

The video camera is the easiest of instruments to be employed on CURIO with an auto-factor of 0.1. The proposed video camera in Table C.2 is probably a specialist video camera, weighing in at 2kg. The author however, proposes the use of a charged-coupled-device (CCD) video camera for various reasons. These being that the CCD video cameras are cheap (costing about £200), small in size (about the size of a common matchbox) and light in weight (about 0.2kg). Furthermore, with the latter two features, the camera can be placed on the end-effector of CURIO rather than some other less attractive location.

Major advantages of placing the video camera on the end-effector include un-obstructive viewing, the ability to zoom and pan, and the ability to measure dimensions of cracks using the distance sensors on CURIO and a computerized ruler based on the viewing distance of the camera to the crack. The unobstructed view of the camera can also add a very powerful feature to the navigations of CURIO by providing a true picture of the surface of the area under inspection at run-time. This feature can really add to the effectiveness of the HMI control center.

Video footage of any inspection can be channeled to a video recorder for storage purposes where upon quality of inspection can be verified and training provided. Snap shots can also be made and stored for quicker access, rather then running through a video tape in a searching process. However, some new video recorders allow the marking of video footage for quicker retrieval. This feature can be computerized with the HMI control center for effective retrieval.

C.4 Half Cell

Half cell measurements are based on the electrochemical nature of reinforcement corrosion (Bungey, 1992). As the name of the instrument suggests, the half cell only constitutes half the electrical circuit and the other half consists of the reinforced concrete structure under test. Figure C.1 shows a schematic of the experimental arrangement of the half cell. The half cell measures the electrical potential of embedded reinforcements relative to itself, which by definition must maintain a ideal constant value of 0. In practice however, a electrical potential of 20mV is acceptable.

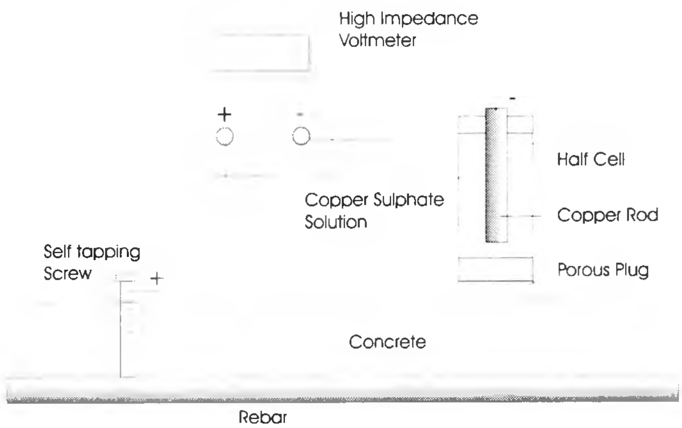


Figure C.1 Schematic of a half cell potential method

For site measurements, the half cell is almost always constructed from of a copper/copper sulphate solution. However, silver/silver chloride cells do exists and are commonly used in research due to their long-term stability. Half cell probes make contact with reinforced concrete structure through a sponge wetted with conductive water. The half cell probe connects to a high impedance voltmeter at one terminal and the other terminal connects to the structural reinforcement using a self tapping screw.

The reinforcement in a structure is usually electrically continuous so that only one electrical connection is needed. However, electrical continuity is not always insured and tests have to be made by drilling in one or more places to test for continuity. In addition, tests have to be made to ensure the total circuit resistance would not exceed 1 Ohm. The concrete structure has also to be tested to determine the need for pre-wetting. This is done by holding the half cell probe on the test surface for about 10 seconds and to check for drift in potential readings. A drift of no more than 10mV is reasonable, above which pre-wetting is required.

By taking measurements over a surface area, a distinction can be made between the corroding and non-corroding locations by means of a contour potential map. The map is built from taking readings on a regular square grid structure, 200mm x 200mm grids sizes are commonly used. Spacing between measurements should generally be reduced where adjacent readings exhibit algebraic reading differences exceeding 150mV. The contour potential map can then be compared with the 'Probability of Corrosion' values as shown in Table C.3 to determine the probable state of corrosion. These values are taken from the ASTM C 876 standard. It should be noted, half cell readings become more negative with increasing moisture content. However, the basic shape of the contours do not vary dramatically with varying dampness.

Table C.3 Probability Criteria for Corrosion Condition

Copper/Copper Sulphate Electrode (mV vs CSE)	Silver/Silver Chloride Electrode (mV vs Ag/AgCl/sat Cl)	Probability of Corrosion
-350 to -500	-260 to -410	95%
-200 to -350	-110 to -260	50%
< -200	< -110	5%

Figure C.2 shows an example contour potential map. The shape of the equi-potential map can provide an indication of the type of corrosion occurring, with a rapid change of contour indicating the possibility of localized pitting. Shallow potential gradients may indicate incipient corrosion.

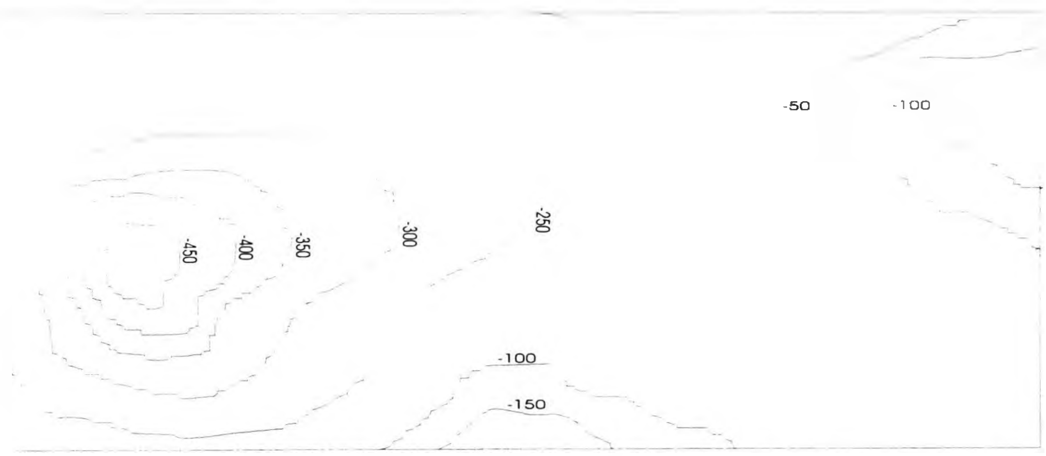


Figure C.2 Contour Potential Plot used to identify areas with high risk of corrosion

Most half-cells equipment today have logging facility, the very latest incorporate the ability to automatically plot equi-potential maps. CANIN from Proceq being one example. Other features include 'multi-cell' and 'wheel' based devices. CANIN's 'wheel' based device has a moistening wheel for continuous wetting up to a length of 200m.

C.5 Acoustic Hammer

The principle of the acoustic hammer test, also commonly known as the impact echo test is based on taking measurements at a concrete surface of the internally reflected shock waves resulting from a single hammer blow (Bungey, 1992). The system consist of three essential components, an impact hammer or an equivalent impact device, a receiving transducer and a signal analyzer. Figure C.3 shows a schematic of the impact echo method.

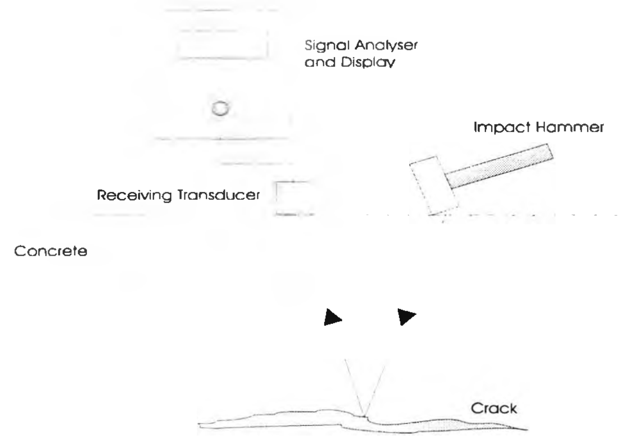


Figure C.3 Pulse Echo Principle

The impact device is used to strike the surface of a test structure, causing shock waves to travel through the immediate surroundings of the concrete structure. If the structure is sound, very little of the impact energy is reflected to the surface. However, in the presence of cracks or voids, a greater proportion of the impact energy is reflected back to the surface from this area. An accelerometer placed on the concrete surface, a small distance away from the impact is used to monitor the reflected impact energy. The output of this is displayed on the signal analyzer, which can be of the form of a digital amplitude reading or an oscilloscope which displays a trace of the shock waves.

An example of the former includes Voidscan by CMT Instruments Ltd. Voidscan is a hand-held device used to detect unseen delaminations and voids within 0.25m of the surface. The device produces depth estimations to within ±5% accuracy. The use of oscilloscopes however, are still generally confined to research establishments.

C.6 Laser Profiler

The linear laser profiler is under research and development at the Construction Robotics Center (Chamberlain, 1994). Figure C.4 shows the laser profiler mounted on a mobile support unit which enables it to be set in various orientations. Whilst higher accuracies in positioning is achievable, the laser profiler has been set to an accuracy of ±1mm in the x - y axes. Profiling rates of the order of 2m/s are achievable.

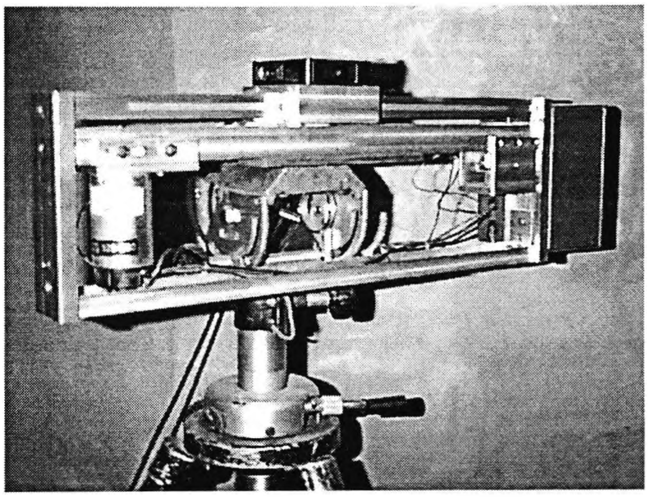


Figure C.4 Laser Profiler mounted on a tripod

The profiler can be used to profile reinforced concrete structures to locate damage and features. On CURIO, a linear laser profiler could also be utilized in determining the terrain of the inspection site. This knowledge can be used by CURIO in avoiding collision during an inspection process.

C.7 Radar

Surface penetrating radar (SPR) is based on comparing the internally reflected microwave signals in concrete structures to the original transmission (Bungey, 1992). Figure C.5 shows a schematic of the SPR equipment. The equipment consists of transmitting and receiving antennae which are usually combined along with a control unit and recorder.

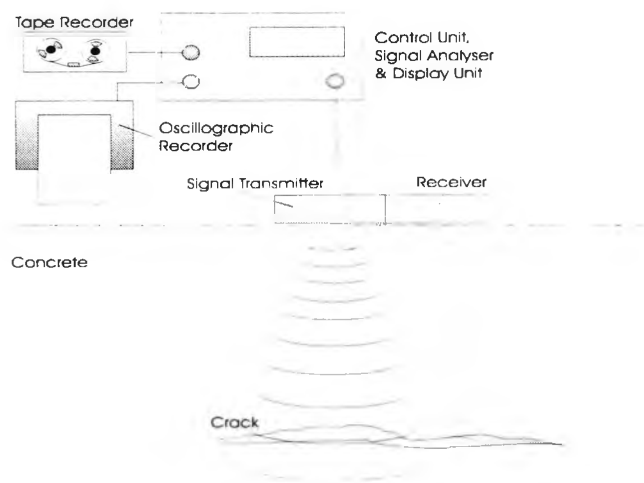


Figure C.5 SPR Setup Configuration

The antennae is placed with its transmitting face parallel to and at a distance of about 0.2m to 0.3m from the surface of the concrete structure. However, if the structure is known to be thick and the penetration of the SPR is not quite sufficient, the antennae may be placed on the surface of the concrete structure. Various settings are made on the control unit and the resulting radar signal is recorded on a calibrated oscillographic recorder.

The resolution of the SPR is dependent on various factors, including signal frequency, pulse duration and antennae configuration. For greater depth of penetration, a combination of lower frequency and larger antennae is required. For example, an 80 MHz signal frequency and 6ns pulse duration combination provides a maximum penetration of approximately 10m. Frequencies up to 10GHz are available with as low as 1ns pulse duration for greater resolution.

The SPR equipment can be used in two modes, stationary and in motion. Figure C.6 depicts the equipment in stationary mode. In the inspection of a sizeable reinforced concrete structure however, the antennae is mounted on an inspection vehicle with a distance measuring device. As the antennae passes through the surface area under inspection, a continuous recording is made on an instrument tape recorder. These recorded signals can then be played back at a later time for data analysis and signal interpretation.

SPR equipment have become popular in recent years and are being used to detect reinforcing bars, changes in moisture content, voids, delaminations, ducts and similar features. All results are on a comparative basis. The equipment however, still requires the attention of experts in testing and especially, interpretation. To assist interpretation, computerized procedures have been developed based on predictions of how the radar wave form may be affected by such varying physical conditions as thickness of concrete, spacing of bars etc. In addition, hardware and software for 3D presentation of SPR readouts are available to aid the process of interpretation (Sensors & Software Inc. Promotional Brochure, 1995).

C.8 Resistivity Meters

Resistivity meters measure the electrical resistance of a reinforced concrete structure by means of a two-probe device or a traditional Wenner four-probe device (Bungey, 1992). With the latter probe (Figure C.6), an alternating low frequency electrical current is passed through the outer electrodes and the voltage drop between the inner electrodes is measured. The two-probe device works on the same principle and is the only method to have been standardized (ASTM D 3633-77).

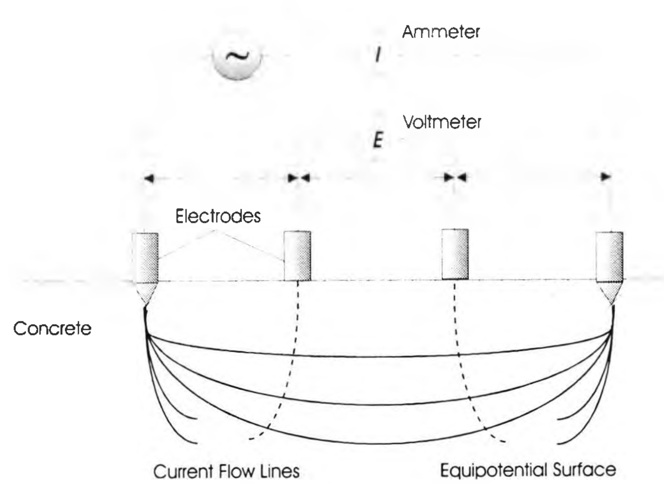


Figure C.6 Four-probe resistivity test layout

Corrosion rate estimations can be obtained from the product of measured reciprocal resistivity and potential gradient (Vassie, 1984). Table C.4 lists the resistivity values that give an indication of the likelihood of significant corrosion based on measured resistivity levels.

Table C.4 Probability criteria for corrosion Resistivity test

Resistivity level (K ohms cm)	Probability of significant reinforcement corrosion
< 5	Certain
5 to 12	Probable
> 12	Unlikely

As in the half cell method, resistivity test interpretations are also based on a comparative method. In fact, resistivity meters are commonly used in conjunction with half cell meters. As resistivity varies slowly over the surface of a structure, its measurement grid tends to be coarser than that of half cell methods. Resistivity measurements are more susceptible to temperature, moisture and salt content and therefore require considerable experience in their interpretation.

C.9 Schmidt Hammer

The quality of concrete is mainly judged by its compressive strength or surface hardness, a property that directly affects the load bearing capacity and durability of concrete structures. The Romans were aware of this fact as they scratched their mortar with a nail to assess its quality. Today, compressive strength measurements are most commonly made by means of rebound hammers, the most popular one being the Schmidt Hammer. This hammer was invented by Ernst Schmidt, a Swiss Engineer in 1948. By 1986, about 50,000 of these hammers were sold worldwide. Today, the Schmidt hammer is one of the most frequently used NDT equipment (Table C.1).

The Schmidt Hammer works on the principle that surface hardness can be measured by the amount of rebound it obtains from a mass impact with a defined energy. The rebound distance is measured on an arbitrary scale (10 - 100) and is represented as 'Rebound Numbers', corresponding to the position of the rider on the scale. Results are effective to within about 30mm of the surface and are influenced by such concrete conditions as surface carbonation hardening, inadequate member rigidity, shallow reinforced cover etc. Determination of uniformity of young concrete structures (less than 3 months old) represents the most reliable field application with a coefficient of variation better than 4% in uniform concrete structures.

Testing can be conducted horizontally, vertically, upwards and at any intermediate angles but the effects of gravity on rebound has to be taken into consideration. Compressive strength conversion diagrams provided with the test hammer by the manufacturers usually provide correlation curves for testing at the horizontal, vertical and upward directions. These conversion strength diagrams however, provide a general conversion as the concrete and testing conditions may not be similar to that in the diagrams. It is therefore strongly recommended that correlation procedures as outlined in BS 1881: Part 201: 1986, section 7 be followed.

There are various types of Schmidt Hammers, each designed for specific test applications. There are 7 different types available from Proceq, of which two are shown in Figure C.7 (a) and (b). Figure C.7(a) shows a Schmidt Hammer with a bar chart paper strip recorder, allowing room for 4000 test impacts per paper roll. Figure C.7(b) depicts a digital Schmidt Hammer (Digi-Schmidt) which allow rebound readings to be read as compressive strength directly. Both hammers comply fully with BS 1881 Part 202.

(a) Original Schmidt Hammer (b) Digi Schmidt

Figure C.7 Proceq Schmidt Hammers

C.10 Thermography

Thermography methods employ infra-red measurements techniques to measure the surface temperature differentials on a concrete structure while heating or cooling (Bungey, 1992). Measurements can be made some distance away from the test structure but extraneous heat sources have to avoided and this includes wind. Commercially available equipment range from hand-held point temperature measuring devices to sophisticated scanner and cathode ray monitor sets providing calibrated colour isotherms which may be video recorded or photographed. The latter tends to be used for large scale surveys as they provide quicker, more detailed acquisition.

Thermography has been successfully used in detecting delamination, locating moisture, major ducts, voids within concrete structures and evaluation of pavements. Like with quite a few of the NDT devices discussed in this chapter, the application of thermography is also based on a comparative methodology. Interpretations require some considerable experience and the use of it in conjunction with radar may be valuable in some circumstances.

Appendix D

(Chapter 10, Section 10.2)

Equation 10.2= Equation 10.4;

$$\frac{A(r)}{(R^2+z^2)^3} = \frac{A(r)}{(a^2+z^2)(b^2+z^2)(a^2+b^2+z^2)}$$

$a = b;$

$$(R^2+z^2)^3 = (a^2+z^2)(a^2+z^2)(2a^2+z^2)$$

$$(R^4+2R^2z^2+z^4)(R^2+z^2) = (a^4+2a^2z^2+z^4)(2a^2+z^2)$$

$$R^6+R^4z^2+2R^4z^2+2R^2z^4+z^6 = 2a^6+a^4z^2+4a^4z^2+2a^2z^4+2a^2z^4+z^6$$

$$R^6+3R^4z^2+3R^2z^4+z^6 = 2a^6+5a^4z^2+4a^2z^4+z^6$$

$\div a^2;$

$$\frac{R^6}{a^2}+\frac{3R^4z^2}{a^2}+\frac{3R^2z^4}{a^2}+\frac{z^6}{a^2} = \frac{2a^6}{a^2}+\frac{5a^4z^2}{a^2}+\frac{4a^2z^4}{a^2}+\frac{z^6}{a^2}$$

If $\frac{z^2}{a^2} = 0;$

$$\frac{R^6}{a^2}+0+0+0 = 2a^4+0+0+0$$

$$\frac{R^6}{a^6} = 2$$

$$\boxed{\frac{R^2}{a^2} = \sqrt[3]{2}}$$

Taking R^4 *& above to equal 0;*

$$0+0+\frac{3R^2z^4}{a^2}+\frac{z^6}{a^2} = \frac{2a^6}{a^2}+\frac{5a^4z^2}{a^2}+\frac{4a^2z^4}{a^2}+\frac{z^6}{a^2}$$

$$\frac{R^2}{a^2}.3z^4 = 2a^4+\frac{5a^4z^2}{a^2}+4a^2z^2.\frac{z^2}{a^2}$$

$$\frac{R^2}{a^2} = \frac{2}{3}.\frac{a^4}{z^4}+\frac{5}{3}.\frac{a^2}{z^2}+\frac{4}{3}$$

If $\frac{z^2}{a^2} = \infty;$

$$\boxed{\frac{R^2}{a^2} = \frac{4}{3}}$$

Appendix E

Traverse Profile Width Method Experimental Equipment

E.1 Introduction

This appendix describes the equipment used in performing the experiments (Chapter 10) that led to the Traverse Profile Width Method employed by the CROCUS and CURIO HMI software in estimating re-bar size and depth-of-cover.

E.2 Hardware

The large number of experiments required in producing and verifying the traverse profile width method, were performed with a Protovale CM5 Covermeter that was manipulated by a CROCUS gantry robot (Figure E.1). The CROCUS robot is a 5-axes robot, consisting of three cartesian axes (x, y, and z) and two revolute axes (yaw and roll). The two revolute axes constitutes yaw about the vertical z-axis and roll at the end-effector. It has a working envelop of 5.0m x 2.5m (x by y respectively) and a z-axis vertical reach of 2m. The closed-loop servo-positioning of the robot's manipulator enables the search probe to be moved and the position measured with high precision. The data-acquisition modules of its control computer enables the CM5 signal strengths to be readily correlated to the probe position.

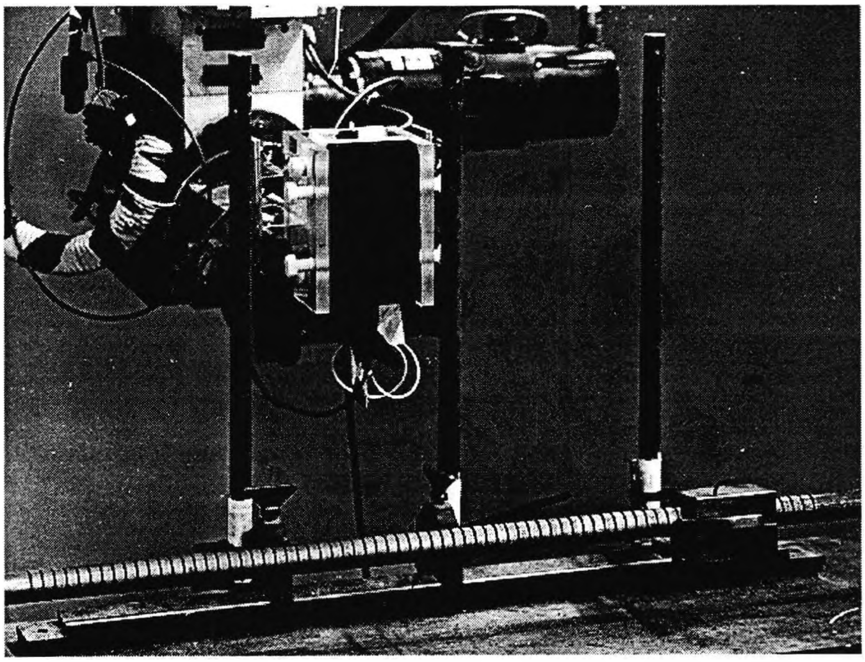


Figure E.1 A photograph of CROCUS performing a traverse scan across three parallel re-bars using a CM5 covermeter

Re-bars to be tested are mounted on metal brackets, which sit on a horizontal metal railing. The railing itself is mounted onto a wooden table (Figure E.1). The brackets allow movement along the railing to permit the re-bars mounted on it to be spaced at varying pitches. Re-bars of about 1m in length were used in all experiments and traverse measurements were made sufficiently distant from the metal railing and brackets to eliminate any influence from them on the CM5 signal readings.

E.3 Software

The software to control the CROCUS robot and the CM5 covermeter were developed in-house by the author. Figure E.2 depicts the control panel of the software application used in performing most of the traverse profile width method experiments. This is discussed in detail in Chapter 11.

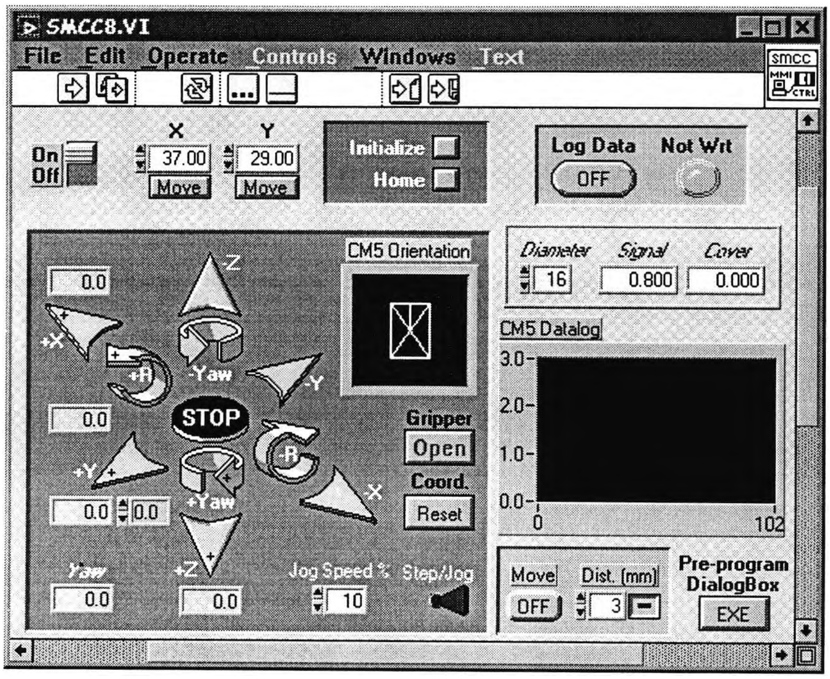


Figure E.2 Software application used in performing the traverse profile width method experiments

Appendix F-1

Experiment 1 : Based on the Traverse Profile Theory of Section 10.2 (Chapter 10).

Objective : To obtain the values of $1/\sqrt[3]{A(r)}$ (Slope) and $\boldsymbol{R^2}$ (Coil Dimension) for each re-bar sizes (8mm, 10mm, 12mm, 16mm & 20mm).

Equipment : Described in Appendix E.

Procedure : The CM5 covermeter head is positioned at the center of the re-bar under test, at the minimum starting distance. As the covermeter head is moved away from the re-bar, signal readings from the covermeter are captured with their corresponding distance to the center of the re-bar. A plot of this is shown in the top graph of Figure 1. The captured data was then analyzed using the application depicted in the figure. The experiment was repeated various times for each re-bar sizes. The results of the experiments are shown in Tables F-1.1 through F-1.7 with the 6th and 7th Tables being additional repeats for re-bar sizes 12mm and 20mm.

Conclusion : Table 10.1 of Section 10.2

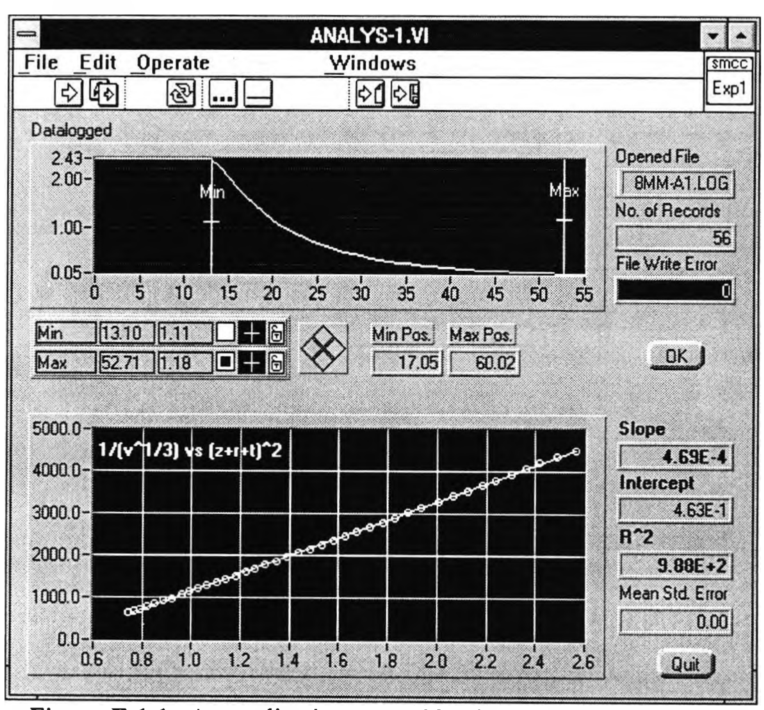


Figure F-1.1 An application created by the author to perform the analysis of Experiment 1

Intermediary Results of Experiment 1

Table F-1.1: 8mm Re-Bar

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
8mm-A1	20.03	44.84	4.75E-04	4.55E-01	9.58E+02
8mm-A2	20.76	44.72	4.74E-04	4.57E-01	9.64E+02
8mm-A3	20.70	44.23	4.76E-04	4.56E-01	9.59E+02
8mm-A4	20.79	44.31	4.75E-04	4.57E-01	9.64E+02
8mm-A5	20.55	44.51	4.75E-04	4.56E-01	9.60E+02
8mm-B1	20.88	44.63	4.79E-04	4.65E-01	9.71E+02
8mm-B2	20.19	44.11	4.79E-04	4.63E-01	9.66E+02
8mm-B3	20.57	44.29	4.80E-04	4.62E-01	9.64E+02
8mm-B4	20.14	44.72	4.79E-04	4.62E-01	9.66E+02
8mm-B5	20.78	44.51	4.78E-04	4.63E-01	9.68E+02
	Mean		**4.77E-04**	**4.60E-01**	**9.64E+02**

Table F-1.2: 10mm Re-Bar

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
10mm-A1	20.28	49.81	4.56E-04	4.38E-01	9.63E+02
10mm-A2	20.23	49.32	4.58E-04	4.41E-01	9.64E+02
10mm-A3	20.76	49.84	4.59E-04	4.50E-01	9.79E+02
10mm-A4	20.44	50.81	4.61E-04	4.51E-01	9.77E+02
10mm-A5	20.44	49.54	4.62E-04	4.53E-01	9.80E+02
10mm-B1	20.90	49.14	4.57E-04	4.44E-01	9.72E+02
10mm-B2	20.63	49.51	4.59E-04	4.44E-01	9.68E+02
10mm-B3	20.88	49.75	4.59E-04	4.46E-01	9.71E+02
10mm-B4	19.96	49.25	4.60E-04	4.46E-01	9.70E+02
10mm-B5	20.41	49.72	4.59E-04	4.52E-01	9.84E+02
10mm-B6	20.28	49.35	4.61E-04	4.49E-01	9.73E+02
	Mean		**4.59E-04**	**4.47E-01**	**9.73E+02**

Table F-1.3: 12mm Re-Bar

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
12mm-A1	25.19	50.21	4.11E-04	4.13E-01	1.00E+03
12mm-A2	25.61	49.35	4.12E-04	4.14E-01	1.01E+03
12mm-A3	25.67	50.05	4.13E-04	4.13E-01	9.99E+02
12mm-A4	25.98	49.70	4.13E-04	4.14E-01	1.00E+03
12mm-A5	25.66	49.84	4.12E-04	4.16E-01	1.01E+03
12mm-A6	25.78	49.73	4.13E-04	4.17E-01	1.01E+03
12mm-B1	25.60	49.34	4.07E-04	3.98E-01	9.79E+02
12mm-B2	25.38	49.13	4.07E-04	3.98E-01	9.77E+02
12mm-B3	25.86	49.38	4.06E-04	4.01E-01	9.88E+02
12mm-B4	25.46	49.42	4.07E-04	4.00E-01	9.84E+02
12mm-B5	25.87	49.81	4.07E-04	4.05E-01	9.95E+02
12mm-B6	25.08	49.67	4.08E-04	4.00E-01	9.81E+02
	Mean		**4.10E-04**	**4.07E-01**	**9.94E+02**

Table F-1.4: 16mm Re-Bar

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
16mm-A1	25.61	54.48	3.49E-04	3.42E-01	9.80E+02
16mm-A2	25.35	54.87	3.52E-04	3.44E-01	9.77E+02
16mm-A3	25.79	54.02	3.50E-04	3.44E-01	9.83E+02
16mm-A4	25.23	55.18	3.51E-04	3.43E-01	9.80E+02
16mm-A5	24.90	55.02	3.52E-04	3.44E-01	9.77E+02
16mm-A6	25.41	54.72	3.50E-04	3.44E-01	9.84E+02
16mm-B1	24.91	55.08	3.55E-04	3.55E-01	9.99E+02
16mm-B2	25.17	54.46	3.49E-04	3.36E-01	9.63E+02
16mm-B3	24.97	55.13	3.50E-04	3.40E-01	9.72E+02
16mm-B4	25.78	54.22	3.51E-04	3.45E-01	9.81E+02
16mm-B5	25.73	55.02	3.50E-04	3.43E-01	9.81E+02
16mm-B6	25.67	54.75	3.50E-04	3.45E-01	9.84E+02
	Mean		**3.51E-04**	**3.44E-01**	**9.80E+02**

Table F-1.5: 20mm Re-Bar

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
20mm-A1	26.01	60.22	3.14E-04	3.21E-01	1.02E+03
20mm-A2	24.78	49.83	3.16E-04	3.21E-01	1.02E+03
20mm-A3	33.67	59.72	3.16E-04	3.21E-01	1.02E+03
20mm-A4	25.29	58.87	3.15E-04	3.23E-01	1.03E+03
20mm-A5	26.13	59.49	3.15E-04	3.22E-01	1.02E+03
20mm-A6	26.10	60.12	3.15E-04	3.23E-01	1.03E+03
20mm-B1	26.04	60.16	3.14E-04	3.28E-01	1.04E+03
20mm-B2	24.96	59.83	3.16E-04	3.29E-01	1.04E+03
20mm-B3	25.87	59.66	3.15E-04	3.32E-01	1.05E+03
20mm-B4	25.82	57.91	3.15E-04	3.29E-01	1.04E+03
20mm-B5	25.05	60.34	3.16E-04	3.29E-01	1.04E+03
20mm-B6	25.61	59.45	3.16E-04	3.28E-01	1.04E+03
	Mean		**3.15E-04**	**3.26E-01**	**1.03E+03**

Table F-1.6: 10mm Re-Bar (Repeat)

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
10mm-A1	20.43	49.10	4.57E-04	4.29E-01	9.38E+02
10mm-A2	20.93	49.60	4.55E-04	4.34E-01	9.53E+02
10mm-A3	20.90	49.13	4.51E-04	4.27E-01	9.47E+02
10mm-A4	20.32	50.25	4.51E-04	4.25E-01	9.43E+02
10mm-B1	20.05	50.19	4.52E-04	4.24E-01	9.40E+02
10mm-B2	20.50	49.16	4.51E-04	4.26E-01	9.45E+02
10mm-B3	20.92	49.57	4.51E-04	4.26E-01	9.46E+02
10mm-B6	20.69	49.98	4.50E-04	4.26E-01	9.47E+02
10mm-B7	20.85	49.72	4.50E-04	4.26E-01	9.45E+02
10mm-C2	50.54	49.81	4.50E-04	4.25E-01	9.44E+02
10mm-C3	20.06	50.24	4.52E-04	4.23E-01	9.37E+02
10mm-C4	20.29	49.37	4.52E-04	4.22E-01	9.33E+02
	Mean		**4.52E-04**	**4.26E-01**	**9.43E+02**

Table F-1.7: 20mm Re-Bar (Repeat)

Filename (*.log)	Min. Dist. (mm)	Max. Dist. (mm)	Slope	Intercept	C^2
20mm-A1	25.35	59.14	3.11E-04	3.03E-01	9.75E+02
20mm-A2	25.54	59.96	3.11E-04	3.01E-01	9.69E+02
20mm-A3	25.02	59.43	3.11E-04	3.02E-01	9.70E+02
20mm-A4	25.40	59.42	3.11E-04	3.01E-01	9.69E+02
20mm-A5	25.19	59.83	3.11E-04	3.02E-01	9.72E+02
20mm-A6	25.49	59.07	3.11E-04	3.02E-01	9.71E+02
20mm-A8	25.16	59.80	3.11E-04	3.01E-01	9.70E+02
20mm-A9	24.96	59.40	3.11E-04	3.01E-01	9.68E+02
20mm-A10	25.95	59.31	3.11E-04	3.01E-01	9.67E+02
	Mean		**3.11E-04**	**3.02E-01**	**9.70E+02**

Table F-1.8: Repeatability of results obtained from scanning 12mm, 16mm, and 20mm re-bars from a predefined cover

Re-bar Diameter (mm)	Cover (mm)	Max. CM5 Reading (mV)	Width, $W_{1/2}$ (mm)
12	36.9	0.391	59.41
	36.9	0.394	59.43
	36.9	0.391	59.41
	36.9	0.391	59.41
16	39.9	0.484	61.57
	39.9	0.485	61.12
	39.9	0.487	60.92
	39.9	0.485	61.57
	39.9	0.485	61.57
20	42.9	0.410	65.44
	42.9	0.410	64.99
	42.9	0.410	64.99
	42.9	0.411	65.01
	42.9	0.410	65.87

Table F-1.9: Summary of Results

Bar size	$1/\sqrt[3]{A(r)}$ (Slope)	Intercept	R^2 (Coil Dimension)
8mm	4.77e-04	4.60e-01	964
10mm (I)	4.59e-04	4.47e-01	973
10mm (II)	4.52e-04	4.26e-01	943
12mm	4.10e-04	4.07e-01	994
16mm	3.51e-04	3.44e-01	980
20mm (I)	3.15e-04	3.26e-01	1030
20mm (II)	3.11e-04	3.02e-01	970

Appendix F-2

Experiment 2 : Based on the Traverse Profile Width Method of Section 10.3 (Chapter 10).

Objective : To obtain a practical equation that relates to a single property of a traverse profile. The width at half-height ($W_{1/2}$).

Equipment : Described in Appendix E.

Procedure : A traverse scan is performed for each re-bar size at varying depth-of-cover to obtain the values of V_{max} and $W_{1/2}$. The results of the experiments are shown in Table F-2.1 through F-2.5.

Conclusion : $z = 1.799\ W_{1/2} - 63.318$ (Equation 10.7) from Figure F-2.2.

Intermediary Results of Experiment 2

Table F-2.1: 8mm Re-Bar

Depth-of-Cover (mm)	CM5 Max. Reading, V_{max} (mV)	Dist. to Center (mm)	Width, $W_{1/2}$ (mm)
22.9	1.206	26.9	50.15
25.9	0.906	29.9	51.64
28.9	0.682	32.9	52.95
31.9	0.515	35.9	54.68
34.9	0.390	38.9	55.32
37.9	0.298	41.9	57.25
40.9	0.230	44.9	59.41

Table F-2.2: 10mm Re-Bar

Depth-of-Cover (mm)	CM5 Max. Reading, V_{max} (mV)	Dist. to Center (mm)	Width, $W_{1/2}$ (mm)
22.9	1.291	27.9	51.240
25.9	0.975	30.9	53.380
28.9	0.736	33.9	53.150
31.9	0.554	36.9	55.320
34.9	0.421	39.9	56.180
37.9	0.321	42.9	59.200
40.9	0.249	45.9	59.840
43.9	0.192	48.9	62.000
46.9	0.151	51.9	63.940
49.9	0.117	54.9	65.870

Table F-2.3: 12mm Re-Bar

Depth-of-Cover (mm)	CM5 Max. Reading, V_{max} (mV)	Dist. to Center (mm)	Width, $W_{1/2}$ (mm)
24.9	1.200	30.9	52.75
27.9	0.964	33.9	54.68
30.9	0.733	36.9	55.34
33.9	0.558	39.9	57.27
36.9	0.428	42.9	58.34
39.9	0.331	45.9	59.85
42.9	0.258	48.9	62.21
45.9	0.207	51.9	64.14
48.9	0.158	54.9	66.31

Table F-2.4: 16mm Re-Bar

Depth-of-Cover (mm)	CM5 Max. Reading, V_{max} (mV)	Dist. to Center (mm)	Width, $W_{1/2}$ (mm)
24.9	1.624	32.9	54.45
27.9	1.182	35.9	56.18
30.9	0.988	38.9	56.84
33.9	0.759	41.9	58.55
36.9	0.586	44.9	59.85
39.9	0.455	47.9	62.23
42.9	0.356	50.9	63.72
45.9	0.280	53.9	65.01
48.9	0.221	56.9	67.40
51.9	0.175	59.9	68.65
54.9	0.140	62.9	70.82

Table F-2.5: 20mm Re-Bar

Depth-of-Cover (mm)	CM5 Max. Reading, V_{max} (mV)	Dist. to Center (mm)	Width, $W_{1/2}$ (mm)
24.9	2.002	34.9	54.90
27.9	1.503	37.9	55.97
30.9	1.155	40.9	58.98
33.9	0.892	43.9	59.21
36.9	0.692	46.9	60.71
39.9	0.542	49.9	62.00
42.9	0.426	52.9	64.80
45.9	0.337	55.9	66.51
48.9	0.267	58.9	68.45
51.9	0.213	61.9	69.75
54.9	0.172	64.9	71.68
57.9	0.139	67.9	73.62

Graphical Analysis of Experimental Results

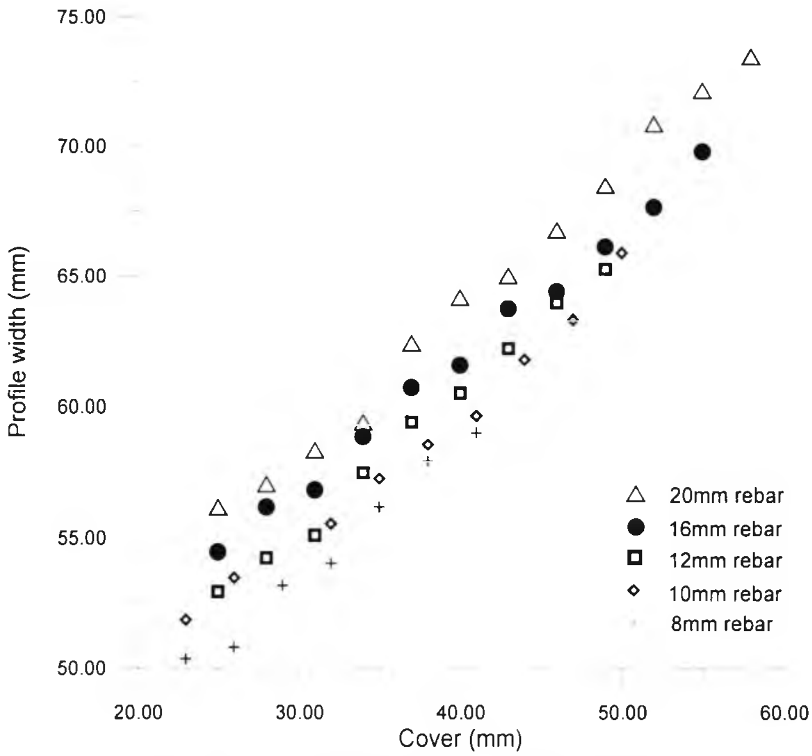


Figure F-2.1 A plot of Profile Width versus Cover

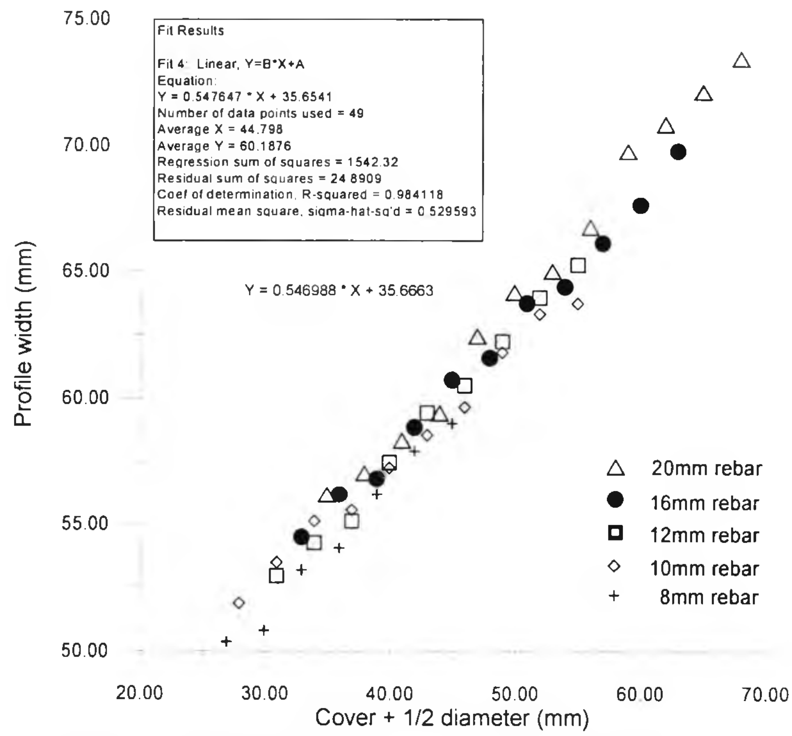


Figure F-2.2 A plot of Profile Width versus Distance-to-Center

Appendix F-3

Traverse Profile Width Method : The result of combining the final results of Experiment 1 (Appendix F1) with Experiment 2 (Appendix F2).

Objective : To test (Results of Experiments) and verify (Random Test) the Traverse Profile Width Method on single re-bars of varying sizes.

Conclusion : The results of the Experiments, tabulated in Table F-3.1 through F-3.5 provides evidence that the Traverse Profile Width Method does have the ability to estimate Diameter and Depth-of-Cover, often within the acceptable accuracy of 5%. Tables F-3.6 through F-3.10 are additional Experimental Results from a Random Testing Experiment.

Results of Experiments

Table F-3.1(a): 8mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
8mm22-9	22.9	50.15	1.206	23.29	1.70	8
8mm25-9	25.9	51.64	0.906	26.11	0.81	8
8mm28-9	28.9	52.95	0.682	28.78	-0.42	8
8mm31-9	31.9	54.68	0.515	31.83	-0.22	8
8mm34-9	34.9	56.41	0.390	34.89	-0.03	8
8mm37-9	37.9	57.25	0.299	37.12	-2.06	8
8mm40-9	40.9	59.41	0.230	40.54	-0.88	8

Table F-3.1(b): 8mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
8mm22-9	22.9	50.37	1.257	23.70	3.49	8
8mm25-9	25.9	51.81	0.945	25.15	-2.90	8
8mm28-9	28.9	53.18	0.710	28.77	-0.45	8
8mm31-9	31.9	54.04	0.580	31.01	-2.79	8
8mm34-9	34.9	56.18	0.409	34.42	-1.38	8
8mm37-9	37.9	57.91	0.313	37.45	-1.19	8
8mm40-9	40.9	59.00	0.242	39.88	-2.49	8

Table F-3.2(a): 10mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
10mm22-9	22.9	51.24	1.291	23.92	4.45	10
10mm25-9	25.9	53.38	0.975	27.29	5.37	10
10mm28-9	28.9	53.15	0.736	28.55	-1.21	8
10mm31-9	31.9	56.61	0.554	33.17	3.98	10
10mm34-9	34.9	56.18	0.421	34.26	-1.83	8
10mm37-9	37.9	59.20	0.321	38.49	1.56	10
10mm40-9	40.9	59.84	0.249	40.48	-1.03	8
10mm43-9	43.9	62.00	0.192	43.92	0.05	8
10mm46-9	46.9	62.85	0.151	46.13	-1.64	8
10mm49-9	49.9	65.87	0.117	50.47	1.14	10

Table F-3.2(b): 10mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
10mm22-9	22.9	51.87	1.301	24.22	5.76	10
10mm25-9	25.9	53.40	0.977	27.29	5.37	10
10mm28-9	28.9	55.11	0.734	30.33	4.95	10
10mm31-9	31.9	55.55	0.556	32.20	0.94	8
10mm34-9	34.9	57.25	0.423	35.20	0.86	8
10mm37-9	37.9	58.55	0.324	37.84	-0.16	8
10mm40-9	40.9	60.71	0.251	41.25	0.86	10
10mm43-9	43.9	61.78	0.193	43.69	-0.48	8
10mm46-9	46.9	63.30	0.151	46.48	-0.90	8
10mm49-9	49.9	64.80	0.120	49.28	-1.24	8

Table F-3.3(a): 12mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
12mm24-9	24.9	52.75	1.200	25.82	3.69	12
12mm27-9	27.9	54.68	0.964	28.72	2.94	12
12mm30-9	30.9	55.34	0.733	30.79	-0.36	12
12mm33-9	33.9	57.27	0.558	34.02	0.35	12
12mm36-9	36.9	58.34	0.428	36.12	-2.11	10
12mm39-9	39.9	59.85	0.331	38.91	-2.48	10
12mm42-9	42.9	62.21	0.258	42.90	0.00	12
12mm45-9	45.9	64.14	0.202	46.15	0.54	12
12mm48-9	48.9	65.22	0.158	48.66	-0.49	12

Table F-3.3(b): 12mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
12mm24-9	24.9	52.95	1.211	25.95	4.22	12
12mm27-9	27.9	54.25	0.943	28.46	2.01	12
12mm30-9	30.9	55.11	0.715	30.47	-1.39	10
12mm33-9	33.9	57.47	0.545	34.33	1.27	12
12mm36-9	36.9	58.77	0.417	37.01	0.30	12
12mm39-9	39.9	60.50	0.323	40.05	0.38	12
12mm42-9	42.9	62.21	0.250	43.10	0.47	12
12mm45-9	45.9	63.94	0.196	46.15	0.54	12
12mm48-9	48.9	65.24	0.155	48.77	-0.27	12

Table F-3.4(a): 16mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
16mm24-9	24.9	54.45	1.624	26.30	5.62	16
16mm27-9	27.9	56.18	1.182	29.59	6.06	16
16mm30-9	30.9	56.84	0.988	31.13	0.74	16
16mm33-9	33.9	58.55	0.759	34.14	0.71	16
16mm36-9	36.9	59.85	0.586	36.78	-0.33	16
16mm39-9	39.9	62.23	0.455	40.38	1.20	16
16mm42-9	42.9	63.72	0.356	43.21	0.72	16
16mm45-9	45.9	65.01	0.280	45.84	-0.13	16
16mm48-9	48.9	67.40	0.221	49.50	1.23	16
16mm51-9	51.9	68.65	0.175	52.12	0.42	16
16mm54-9	54.9	70.82	0.140	55.59	1.26	16

Table F-3.4(b): 16mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
16mm24-9	24.9	54.47	1.780	25.83	3.73	16
16mm27-9	27.9	56.18	1.065	30.13	7.99	16
16mm30-9	30.9	56.82	0.973	31.20	0.97	16
16mm33-9	33.9	58.55	0.813	33.75	-0.44	16
16mm36-9	36.9	60.71	0.589	37.52	1.68	16
16mm39-9	39.9	61.57	0.484	39.43	-1.18	16
16mm42-9	42.9	63.72	0.378	42.88	-0.05	16
16mm45-9	45.9	64.37	0.298	44.88	-2.22	16
16mm48-9	48.9	66.10	0.235	47.93	-1.98	16
16mm51-9	51.9	67.60	0.185	50.82	-2.08	16
16mm54-9	54.9	69.75	0.147	54.29	-1.11	16

Table F-3.5(a): 20mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
20mm24-9	24.9	54.90	2.002	25.59	2.77	20
20mm27-9	27.9	55.97	1.503	28.10	0.72	20
20mm30-9	30.9	58.98	1.155	32.26	4.40	20
20mm33-9	33.9	59.21	0.892	33.93	0.09	20
20mm36-9	36.9	60.71	0.692	36.74	-0.43	20
20mm39-9	39.9	62.00	0.542	39.16	-1.85	20
20mm42-9	42.9	64.80	0.426	43.35	1.05	20
20mm45-9	45.9	66.51	0.337	46.36	1.00	20
20mm48-9	48.9	68.45	0.267	49.61	1.45	20
20mm51-9	51.9	69.75	0.213	52.27	0.71	20
20mm54-9	54.9	71.68	0.172	55.48	1.06	20
20mm57-9	57.9	73.62	0.139	58.74	1.45	20

Table F-3.5(b): 20mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover (mm)	Width $W_{1/2}$	V_{max}	Estimated Cover (mm)	Percentage Error	Estimated Diameter
20mm24-9	24.9	56.18	1.828	27.23	9.36	20
20mm27-9	27.9	57.05	1.442	29.30	5.02	20
20mm30-9	30.9	58.34	1.113	31.89	3.20	20
20mm33-9	33.9	59.41	0.858	34.32	1.24	20
20mm36-9	36.9	62.42	0.669	38.49	4.31	20
20mm39-9	39.9	64.15	0.522	41.52	4.06	20
20mm42-9	42.9	65.44	0.410	44.15	2.91	20
20mm45-9	45.9	66.74	0.327	46.75	1.85	20
20mm48-9	48.9	69.75	0.258	50.99	4.27	20
20mm51-9	51.9	70.82	0.206	53.46	3.01	20
20mm54-9	54.9	72.11	0.166	56.11	2.20	20
20mm57-9	57.9	73.42	0.134	58.81	1.57	20

Results from a Random Testing Experiment

Table F-3.6(a): 20mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
20mm31	31	33.18	7.03	20
20mm34	34	36.01	5.91	20
20mm40	40	41.51	3.78	20
20mm45	45	46.62	3.60	20
20mm50	50	52.85	5.70	20
20mm60	60	64.79	7.98	20

Table F-3.6(b): 20mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
20mm30-8	30.8	31.73	3.02	20
20mm33-8	33.8	34.35	1.63	20
20mm39-8	39.8	40.79	2.49	20
20mm44-8	44.8	45.34	1.21	20
20mm49-8	49.8	51.51	3.43	20
20mm59-8	59.8	62.03	3.73	20

Table F-3.7: 16mm Re-bar

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
16mm27-9	27.9	28.67	2.76	16
16mm30-9	30.9	31.51	1.97	16
16mm33-9	33.9	34.89	2.92	16
16mm38-9	38.9	38.69	-0.54	16
16mm43-9	43.9	44.91	2.30	16
16mm55-9	55.9	55.20	-1.25	16

Table F-3.8(a): 12mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
12mm26-7	26.7	27.34	2.40	12
12mm29-7	29.7	30.20	1.68	12
12mm32-7	32.7	32.68	-0.06	12
12mm37-7	37.7	38.06	0.95	12
12mm42-7	42.7	44.12	3.33	12
12mm47-7	47.7	48.35	1.36	12

Table F-3.8(b): 12mm Re-bar (Batch 2)
Curved at center of re-bar by about 1mm

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
12mm25-9	25.9	28.30	9.27	12
12mm28-9	28.9	29.55	2.25	12
12mm31-9	31.9	31.39	-1.60	12
12mm36-9	36.9	37.80	2.44	12
12mm41-9	41.9	43.88	4.73	12
12mm46-9	46.9	48.73	3.90	12

Table F-3.9: 10mm Re-bar
A slightly curved re-bar

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
10mm22-7	22.7	24.72	8.90	10
10mm25-7	25.7	25.96	1.01	8
10mm28-7	28.9	29.35	1.56	10
10mm31-7	31.7	30.82	-2.78	8
10mm36-7	36.7	36.38	-0.87	8
10mm41-7	41.7	41.05	-1.56	8
10mm46-7	46.7	46.87	0.36	8

Table F-3.10(a): 8mm Re-bar (Batch 1)

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
8mm22-1	22.1	23.16	4.80	8
8mm25-1	25.1	24.78	-1.27	8
8mm28-1	28.1	27.62	-1.71	8
8mm31-1	31.1	29.90	-3.86	8
8mm34-1	34.1	32.72	-4.05	8
8mm37-1	37.1	36.35	-2.02	8
8mm40-1	40.1	39.73	-0.92	8

Table F-3.10(b): 8mm Re-bar (Batch 2)

Filename (*.log)	Actual Cover	Estimated Cover	Percentage Error	Estimated Diameter
8mm23-2	23.2	24.74	6.64	10
8mm26-2	26.2	26.70	1.91	8
8mm29-2	29.2	29.17	-0.10	8
8mm32-2	32.2	31.27	-2.89	8
8mm35-2	35.2	35.27	0.20	8
8mm38-2	38.2	37.36	-2.20	8

Appendix F-4

Experiment 3 : Effects of Parallel Re-Bars on the Traverse Profile Width Method, Section 10.5.

Objective : To determine the effects of neighboring re-bars on the Traverse Profile Width Method and to extend the Traverse Profile Width Method to take account of such cases. Experiments I and II were performed to determine the effects of pitch on the properties of a traverse profile reading. Experiments III and IV were performed to determine the values of Q, and Experiment V to determine the value of n (see Section 10.5).

Equipment : Described in Appendix E.

Procedure : A traverse scan is performed on parallel re-bar of the same size, at varying pitches and at varying depth-of-covers to determine the their effects on the Traverse Profile Width Method of section 10.3.

Conclusion : Width measurements ($W_{V_{meas}}$) are taken at $v_{meas} = {}^{1}/_{2}v_{max}[1 + (v_{min}/v_{max})^2]$ instead of ${}^{1}/_{2}v_{max}$.

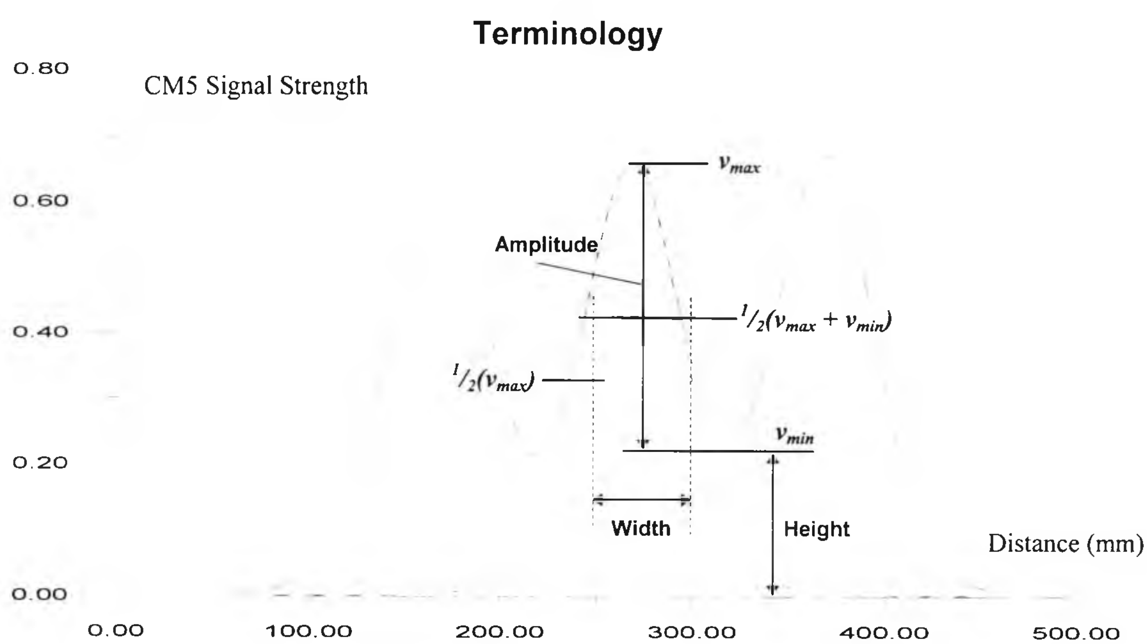


Figure F-4.1 The effects of neighboring parallel re-bars on the traverse profile of the central re-bar

Results of Experiments

Experiment I (12mm Re-bars)

Table F-4.1(I): Pitch of 100mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
229	0.19	0.881	48.01	1.071	21.98	25
256	0.15	0.514	48.01	0.664	24.48	30
300	0.12	0.307	48.21	0.427	27.02	35
303	0.09	0.182	49.28	0.272	30.49	40
305	0.07	0.116	48.87	0.186	32.30	45

Table F-4.2(I): Pitch of 120mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
323	0.07	0.992	51.44	1.062	25.10	25
325	0.06	0.602	51.45	0.662	27.59	30
327	0.06	0.366	52.74	0.426	31.11	35
332	0.05	0.223	54.47	0.273	35.13	40
334	0.04	0.145	55.54	0.185	38.33	45

Table F-4.3(I): Pitch of 140mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
346	0.03	1.037	53.40	1.067	27.02	25
352	0.03	0.615	54.90	0.645	30.82	30
356	0.03	0.385	57.04	0.415	35.11	35
359	0.02	0.247	58.97	0.267	39.30	40
402	0.02	0.160	60.70	0.180	43.12	45

Table F-4.4(I): Pitch of 160mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
408	0.01	1.044	53.38	1.054	27.07	25
415	0.01	0.646	55.97	0.656	31.96	30
417	0.01	0.412	57.68	0.422	35.61	35
420	0.01	0.260	59.62	0.270	39.82	40
424	0.01	0.173	62.21	0.183	44.41	45

Table F-4.5(I): Pitch of 180mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
432	0	1.049	53.61	1.049	27.30	25
435	0	0.646	55.75	0.646	31.58	30
436	0	0.415	58.77	0.415	37.04	35
437	0	0.267	60.50	0.267	40.71	40
438	0	0.179	62.44	0.179	44.73	45

Table F-4.6(I): Pitch of 200mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
445	0	1.042	53.40	1.042	27.15	25
447	0	0.645	55.97	0.645	31.78	30
449	0	0.416	58.34	0.416	36.28	35
451	0	0.268	60.94	0.268	41.08	40
453	0	0.180	63.94	0.180	46.10	45

Table F-4.7(I): Pitch of 220mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
501	0	1.049	53.84	1.049	27.51	25
502	0	0.649	56.84	0.649	32.81	30
504	0	0.419	57.88	0.419	35.83	35
505	0	0.268	60.94	0.268	41.58	40
506	0	0.180	63.71	0.180	45.90	45

Table F-4.8(I): Pitch of 240mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
512	0	1.059	53.60	1.059	27.24	25
515	0	0.636	56.61	0.636	32.71	30
516	0	0.409	58.57	0.409	36.58	35
518	0	0.264	61.14	0.264	41.34	40
520	0	0.178	64.15	0.178	46.38	45

Table F-4.9(I): Pitch of 260mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
525	0	1.028	54.25	1.028	27.99	25
530	0	0.636	55.54	0.636	31.47	30
531	0	0.410	58.55	0.410	36.55	35
533	0	0.264	62.42	0.264	42.96	40
534	0	0.179	64.15	0.179	46.34	45

Experiment II (20mm Re-bars)

Table F-4.10(II): Pitch of 80mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
133	0.54	0.500	41.11	1.040	15.95	30
135	0.39	0.285	41.11	0.675	18.19	35
143	0.29	0.159	41.52	0.449	19.78	40
144	0.22	0.101	41.11	0.321	23.18	45
145	0.16	0.063	41.97	0.223	25.05	50

Table F-4.11(II): Pitch of 100mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
149	0.28	0.741	48.01	1.040	22.04	30
157	0.28	0.722	48.00	1.002	22.31	35
200	0.21	0.440	48.67	0.650	25.18	40
202	0.13	0.174	48.44	0.304	29.11	45
204	0.10	0.109	48.87	0.209	31.63	50

Table F-4.12(II): Pitch of 120mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
210	0.14	0.902	54.02	1.042	27.71	30
215	0.11	0.563	54.45	0.673	30.19	35
217	0.09	0.355	55.74	0.445	33.57	40
218	0.08	0.231	56.40	0.311	36.13	45
220	0.06	0.153	56.40	0.213	38.27	50

Table F-4.13(II): Pitch of 140mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
225	0.07	0.953	57.48	1.023	31.52	30
230	0.05	0.613	59.62	0.663	35.87	35
232	0.05	0.389	60.27	0.439	38.07	40
233	0.04	0.266	61.58	0.306	41.34	45
235	0.04	0.169	62.64	0.209	45.56	50

Table F-4.14(II): Pitch of 160mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
240	0.03	0.979	57.05	1.009	32.16	30
250	0.03	0.623	60.05	0.653	36.33	35
252	0.02	0.412	62.64	0.432	41.07	40
254	0.02	0.279	64.15	0.299	44.67	45
255	0.02	0.185	66.07	0.205	48.77	50

Table F-4.15(II): Pitch of 180mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
300	0.01	1.052	58.32	1.062	32.14	30
306	0.01	0.673	61.14	0.683	37.21	35
307	0.01	0.441	62.42	0.451	40.62	40
308	0.01	0.303	65.01	0.313	45.15	45
310	0.01	0.203	67.81	0.213	50.08	50

Table F-4.16(II): Pitch of 200mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
315	0	1.048	57.91	1.048	31.84	30
323	0	0.676	60.28	0.676	36.35	35
325	0	0.447	63.07	0.447	41.25	40
327	0	0.309	65.87	0.309	45.99	45
328	0	0.211	68.47	0.211	50.74	50

Table F-4.17(II): Pitch of 220mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
335	0	1.028	58.77	1.028	32.72	30
344	0	0.663	61.57	0.663	37.77	35
346	0	0.440	64.35	0.440	42.74	40
347	0	0.305	67.17	0.305	47.59	45
350	0	0.208	70.17	0.208	52.83	50

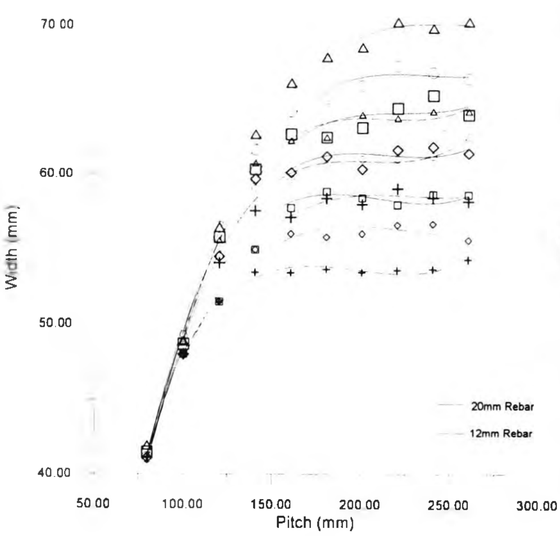
Table F-4.18(II): Pitch of 240mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
355	0	1.015	58.34	1.015	32.41	30
405	0	0.653	61.78	0.653	38.05	35
407	0	0.432	65.22	0.432	43.65	40
409	0	0.298	66.74	0.298	47.36	45
410	0	0.204	69.75	0.204	52.57	50

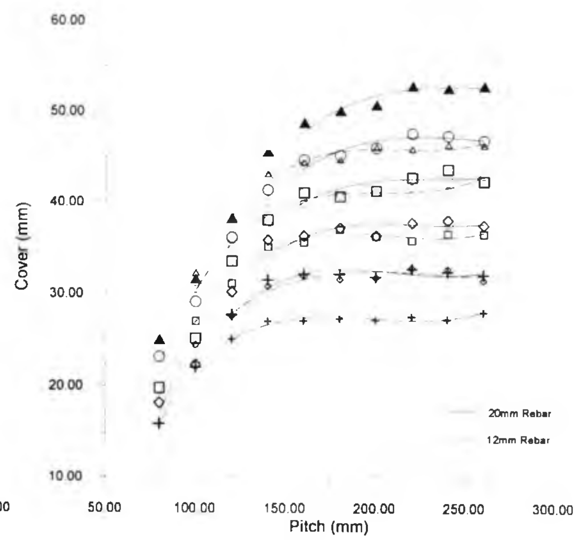
Table F-4.19(II): Pitch of 260mm

File(*.log)	Height	Amplitude	Width	Max CM5	Cover	Cover (Actual)
420	0	1.039	58.11	1.039	32.07	30
424	0	0.668	61.34	0.668	37.52	35
426	0	0.441	63.92	0.441	42.34	40
428	0	0.305	66.33	0.305	46.83	45
430	0	0.209	70.18	0.209	52.80	50

Graphical Analysis of Experiments I and II



(a) Plot of Width versus Pitch



(b) Plot of Cover versus Pitch

Figure F-4.2 The variation of width and cover against pitch for parallel 12mm and 20mm re-bars

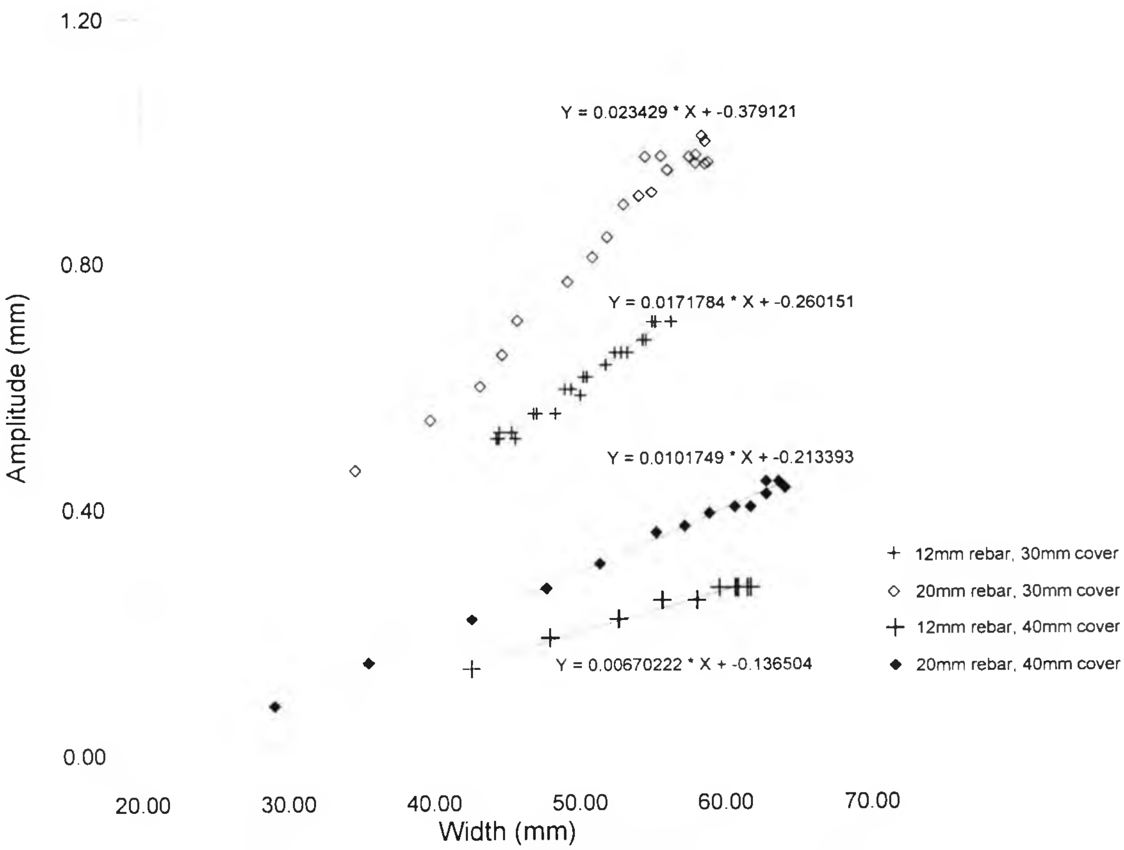


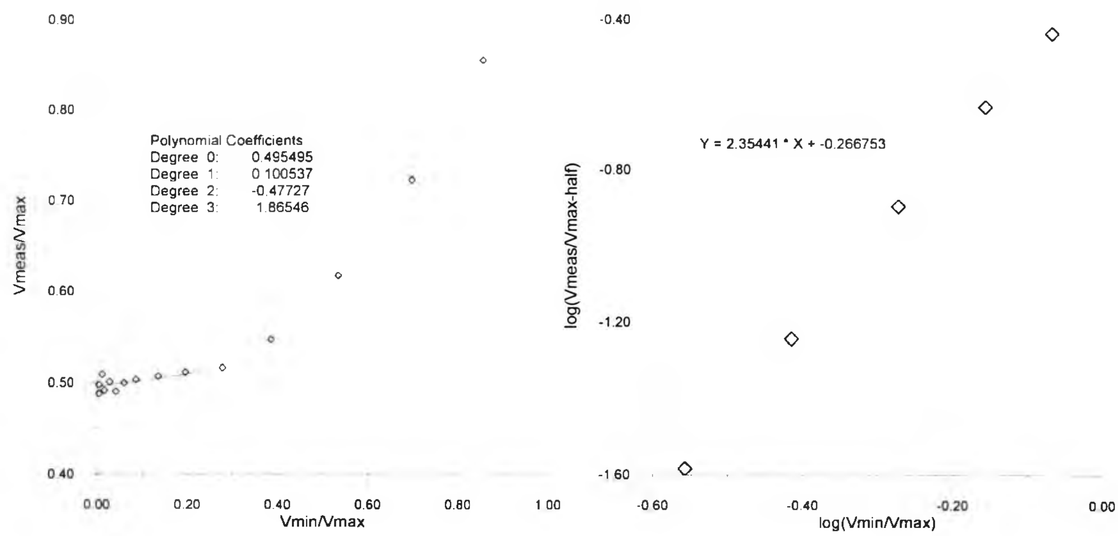
Figure F-4.3 Plot of Amplitude (mm) vs. Width (mm) for covers of 30mm & 40mm

Experiment III

Table F-4.20(III): 12mm re-bars at 36mm cover

Pitch	V_{max}	V_{min}	$V_{measure}$	V_{meas} / V_{max}	V_{min} / V_{max}	log[(V_{meas} / V_{max}) - 0.5]	log[(V_{meas} / V_{max}) - 0.49]	log [V_{min} / V_{max}]
60	0.481	0.411	0.411	0.8545	0.8545	-0.4504	-0.4383	-0.0683
70	0.454	0.316	0.328	0.7225	0.6960	-0.6527	-0.6336	-0.1574
80	0.441	0.235	0.272	0.6168	0.5329	-0.9326	-0.8969	-0.2734
90	0.437	0.168	0.239	0.5469	0.3844	-1.3288	-1.2449	-0.4154
100	0.436	0.121	0.225	0.5161	0.2775	-1.7932	-1.5834	-0.5567
110	0.436	0.085	0.223	0.5115	0.1950	-1.9393	-1.6676	-0.7100
120	0.422	0.057	0.214	0.5071	0.1351	-2.1487	-1.7670	-0.8693
130	0.431	0.037	0.217	0.5035	0.0858	-2.4559	-1.8697	-1.0665
140	0.434	0.026	0.217	0.5000	0.0599	NAN	-2.0000	-1.2526
150	0.434	0.018	0.213	0.4908	0.0415	NAN	-3.0969	-1.3820
160	0.431	0.012	0.216	0.5012	0.0278	NAN	-1.9508	-1.5560
170	0.431	0.007	0.212	0.4919	0.0162	NAN	-2.7212	-1.7905
180	0.430	0.005	0.219	0.5093	0.0116	NAN	-1.7145	-1.9344
190	0.432	0.002	0.211	0.4884	0.0046	NAN	NAN	-2.3344
200	0.430	0.002	0.214	0.4978	0.0046	NAN	-2.1079	-2.3325

Graphical Analysis of Experiment III
(From Table F-4.20(III))



(a) Plot of v_{meas}/v_{max} vs. v_{min}/v_{max} (b) Plot of log(v_{meas}/v_{max} - half) vs. log(v_{min}/v_{max})

Figure F-4.4 Plots to determine the value of Q using a 12mm re-bar at 36mm cover

Experiment III (Continued)

Table F-4.21(III): 12mm Re-bars at 36mm Cover

Filename (*.log)	Measured Pitch	V_{max}	V_{min}	Width (V_{max})	Width (V_{max} + V_{min})	$V_{measure}$	Q	Estimated Re-bar Size	Estimated Cover
255	60	0.342	0.292	64.60	33.58	0.292	0.829	8	15.08
450	70	0.323	0.225	82.90	37.67	0.233	0.638	8	19.08
445	80	0.314	0.167	101.82	41.55	0.193	0.432	8	22.74
440	90	0.311	0.120	64.58	45.85	0.170	0.248	8	26.65
430	100	0.310	0.086	62.42	49.30	0.160	0.118	8	29.76
425	110	0.310	0.059	60.27	52.52	0.159	0.114	8	32.66
330	120	0.300	0.041	59.85	54.47	0.153	0.125	8	34.59
335	130	0.307	0.026	59.61	55.32	0.154	0.065	8	35.24
345	140	0.309	0.019	59.43	57.07	0.154	0.000	8	36.77
350	150	0.309	0.012	59.85	57.68	0.152	-0.429	8	37.32
355	160	0.307	0.008	59.64	57.48	0.153	0.000	8	37.18
400	170	0.307	0.005	59.20	58.12	0.151	-1.000	8	37.75
410	180	0.306	0.003	58.98	58.98	0.156	1.750	8	38.54
415	190	0.308	0.002	58.32	58.32	0.150	-4.500	8	37.92
420	200	0.306	0.002	58.98	58.98	0.153	-0.500	8	38.54
Single Re-bar 453	N/A	0.307	0	59.64	59.64	0.141	N/A	10	39.14

Table F-4.21(III): (Continued)

Measured Pitch	V_{max}	V_{min}	1/Pitch	V_{min}/V_{max}	Width (V_{max})	Width (V_{max} + V_{min})	Q	V_{meas}/V_{max}	$(V_{min}/V_{max})^2$
60	0.342	0.292	16.667	0.8538	64.60	33.58	0.1599	0.8538	0.72897
70	0.323	0.225	14.285	0.6965	82.90	37.67	0.5143	0.7213	0.48524
80	0.314	0.167	12.500	0.5318	101.82	41.55	0.6998	0.6146	0.28286
90	0.311	0.120	11.111	0.3858	64.58	45.85	0.2637	0.5466	0.14888
100	0.310	0.086	10.000	0.2774	62.42	49.30	0.2118	0.5161	0.07696
110	0.310	0.059	9.0909	0.1903	60.27	52.52	0.0813	0.5129	0.03622
120	0.300	0.041	8.3333	0.1366	59.85	54.47	0.0390	0.5100	0.01867
130	0.307	0.026	7.6923	0.0846	59.61	55.32	-0.0069	0.5016	0.00717
140	0.309	0.019	7.1429	0.0614	59.43	57.07	-0.0889	0.4983	0.00378
150	0.309	0.012	6.6667	0.0388	59.85	57.68	0.0968	0.4919	0.00150
160	0.307	0.008	6.2500	0.0260	59.64	57.48	0.0000	0.4983	0.00067
170	0.307	0.005	5.8823	0.0162	59.20	58.12	-0.4074	0.4918	0.00026
180	0.306	0.003	5.5556	0.0098	58.98	58.98	#DIV/0!	0.5098	9.611E-05
190	0.308	0.002	5.2631	0.0065	58.32	58.32	#DIV/0!	0.4870	4.216E-05
200	0.306	0.002	5.0000	0.0065	58.98	58.98	#DIV/0!	0.5000	4.271E-05

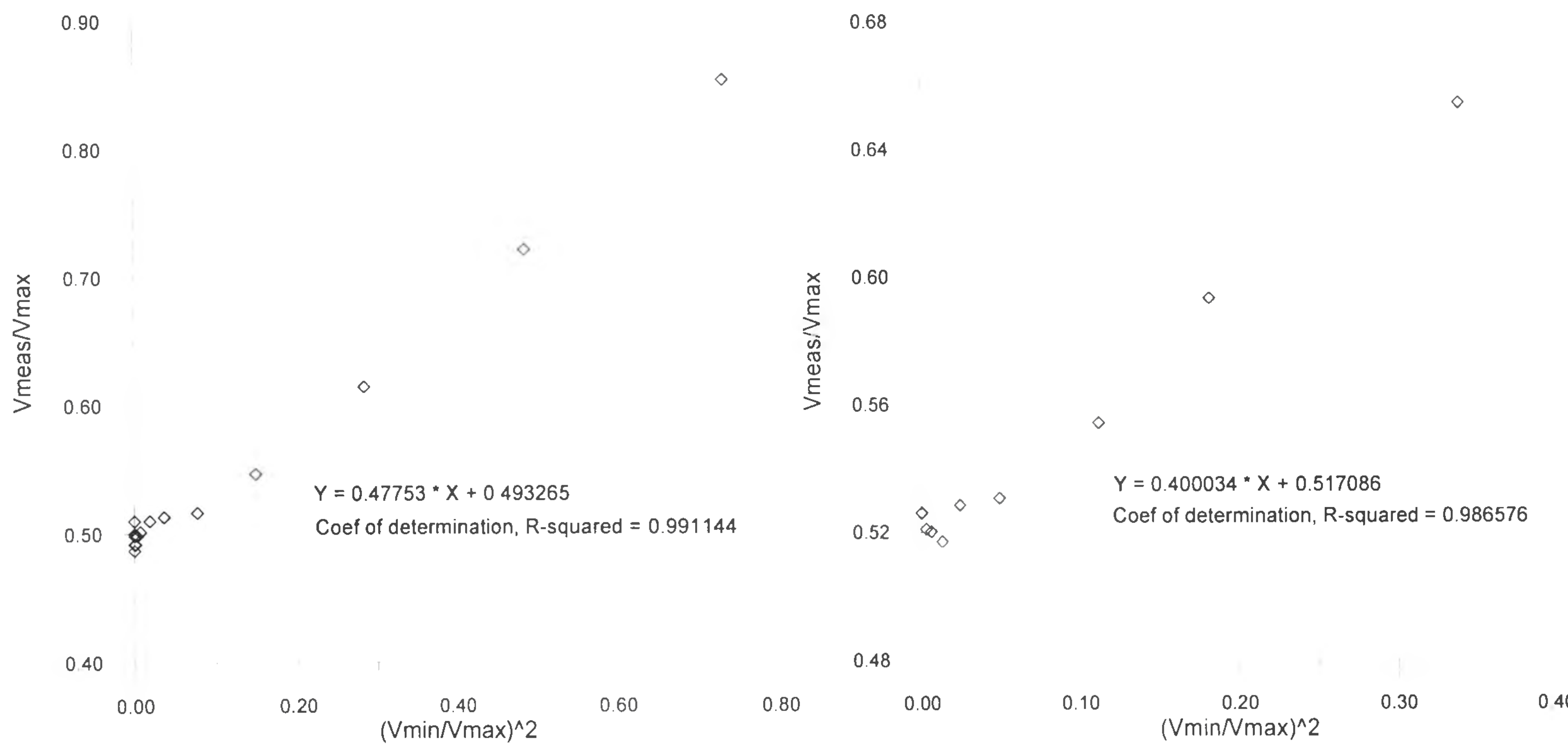
Table F-4.22(III): 20mm Re-bar at various Covers

Filename	Cover	Pitch	V_{max}	V_{min}	Width (V_{max})	Width (V_{max} + V_{min})	$V_{measure}$	Q	Estimated Re-bar size	Estimated Cover
300	36	80	0.709	0.413	93.21	41.10	0.464	0.533	8	17.92
305	40	80	0.479	0.305	92.99	41.55	0.336	0.633	8	20.42
307	45	80	0.329	0.225	91.91	41.98	0.247	0.730	8	22.86
319	36	90	0.713	0.304	69.94	46.27	0.423	0.435	8	22.53
321	40	90	0.479	0.231	108.28	46.94	0.298	0.505	8	25.26
323	45	90	0.324	0.176	102.66	46.30	0.217	0.622	8	26.82
331	36	100	0.628	0.210	67.38	49.94	0.348	0.324	8	26.51
335	40	100	0.423	0.163	72.54	50.80	0.256	0.547	8	29.40
339	45	100	0.288	0.127	80.74	50.58	0.186	0.654	8	31.33
350	36	110	0.684	0.152	62.88	54.04	0.363	0.281	8	29.74
355	36	120	0.685	0.107	62.00	55.52	0.362	0.367	8	31.06
410	36	130	0.673	0.077	62.87	57.48	0.348	0.292	12	33.18
420	36	140	0.692	0.054	62.85	58.55	0.360	0.511	16	34.66
422	40	140	0.481	0.048	65.88	60.40	0.258	1.175	16	38.74
425	45	140	0.313	0.040	68.02	61.57	0.186	1.441	12	41.19
430	36	150	0.691	0.037	61.57	59.41	0.360	0.774	16	35.44
435	36	200	0.692	0.006	61.57	61.57	0.364	6.200	20	37.52
Single Re-bar 440	36	N/A	0.688	0.005	62	62	0.363	N/A	20	37.93

Table F-4.22(III): (Continued)

Pitch	1/Pitch	V_{max}	V_{min}	Width (V_{max})	Width (V_{max} + V_{min})	V_{min}/ V_{max}	Q	$V_{measure}$/ V_{max}	$(V_{min}/V_{max})^2$
80	12.50	0.709	0.413	93.21	41.10	0.5825	0.5989	0.6544	0.3393
80	12.50	0.479	0.305	92.99	41.55	0.6367	0.6024	0.7015	0.4054
80	12.50	0.329	0.225	91.91	41.98	0.6839	0.5990	0.7508	0.4677
90	11.11	0.713	0.304	69.94	46.27	0.4264	0.3354	0.5933	0.1818
90	11.11	0.479	0.231	108.28	46.94	0.4823	0.7545	0.6221	0.2326
90	11.11	0.324	0.176	102.66	46.30	0.5432	0.7214	0.6698	0.2951
100	10.00	0.628	0.210	67.38	49.94	0.3344	0.3084	0.5541	0.1118
100	10.00	0.423	0.163	72.54	50.80	0.3853	0.4848	0.6052	0.1485
100	10.00	0.288	0.127	80.74	50.58	0.4410	0.6215	0.6458	0.1945
110	9.09	0.684	0.152	62.88	54.04	0.2222	0.0995	0.5307	0.0494
120	8.33	0.685	0.107	62.00	55.24	0.1562	0.0000	0.5285	0.0244
130	7.69	0.673	0.077	62.87	57.48	0.1144	0.1614	0.5171	0.0131
140	7.14	0.692	0.054	62.85	58.55	0.0780	0.1977	0.5202	0.0061
140	7.14	0.481	0.048	65.88	60.40	0.0998	0.7080	0.5364	0.0100
140	7.14	0.313	0.040	68.02	61.57	0.1278	0.9333	0.5942	0.0163
150	6.67	0.691	0.037	61.57	59.41	0.0535	-0.1991	0.5210	2.87E-03
200	5.00	0.692	0.006	61.57	61.57	0.0087	#DIV/0!	0.5260	7.53E-05

Graphical Analysis of Experiment III
(From Tables F-4.21(III) & F-4.22(III))



(a) Plot for 12mm re-bars at 36mm cover (b) Plot for 20mm re-bars at 36mm cover

Figure F-4.5 Plots of (v_{meas}/v_{max}) versus $(v_{min}/v_{max})^2$ for 12mm and 20mm re-bars

Experiment IV

Table F5.23(IV): Calc. $V_{meas} = ½\, V_{max}(1+R^{n})$; n = 1.7 — 12mm re-bar at 35mm cover

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover
255	60	0.481	0.411	0.411	0.425	60.71	16	38.70	V_{max} < 2 33.58	8	13.22
						60.71	16	38.70	46.70	8	25.01
450	70	0.454	0.316	0.328	0.349	70.17	20	47.78	V_{max} < 2 37.67	8	17.21
						58.57	12	36.36	48.42	8	26.88
445	80	0.441	0.235	0.272	0.296	82.86	20	59.38	V_{max} < 2 41.55	8	20.87
						59.41	12	37.28	52.75	8	30.93
440	90	0.437	0.168	0.239	0.262	64.58	20	42.99	45.85	8	24.78
						60.28	12	38.11	54.68	8	32.71
430	100	0.436	0.121	0.225	0.243	62.42	16	40.82	49.30	8	27.88
						60.28	12	38.12	55.75	8	33.69
425	110	0.436	0.085	0.223	0.231	60.27	12	38.11	51.44	8	29.81
						59.18	12	37.13	58.12	10	35.83
330	120	0.422	0.057	0.214	0.218	59.85	12	37.93	54.47	8	32.71
						59.85	12	37.93	58.78	12	36.97
335	130	0.431	0.037	0.217	0.219	59.61	12	37.58	55.32	8	33.36
						59.61	12	37.58	59.31	12	37.58
345	140	0.434	0.026	0.217	0.219	59.34	12	37.38	57.07	8	34.90
						59.43	12	37.38	59.43	12	37.38
350	150	0.434	0.018	0.213	0.218	59.85	12	37.77	57.68	10	35.46
						59.85	12	37.77	59.85	12	37.77
355	160	0.431	0.012	0.216	0.216	59.64	12	37.61	57.48	10	35.31
						59.64	12	37.61	59.64	12	37.61
400	170	0.431	0.007	0.212	0.216	59.20	12	37.21	58.12	10	35.89
						60.50	12	38.38	59.20	12	37.21

Table F5.23(IV): Calc. $V_{meas} = ½ V_{max}(1+R^{n})$; n = 1.7 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover
410	180	0.430	0.005	0.219	0.215	58.98	12	37.03	58.98	12	37.03
						58.98	12	37.03	58.98	12	37.03
415	190	0.432	0.002	0.211	0.216	58.32	10	36.05	58.32	10	36.05
						60.50	12	38.36	58.32	10	36.05
420	200	0.430	0.002	0.214	0.215	58.98	12	37.03	58.98	12	37.03
						60.05	12	38.00	58.98	12	37.03

Table F5.24(IV): Calc. $V_{meas} = ½ V_{max}(1+R^{n})$; n = 1.9 12mm re-bar at 35mm cover

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover
255	60	0.481	0.411	0.411	0.419	58.12	12	35.63	$V_{max} < 2 V_{min}$ 33.58	8	13.22
						58.12	12	35.63	50.58	8	28.51
450	70	0.454	0.316	0.328	0.341	71.25	20	48.76	$V_{max} < 2$ 37.67	8	17.21
						58.57	12	36.36	52.11	8	30.2
445	80	0.441	0.235	0.272	0.287	79.85	20	56.67	$V_{max} < 2$ 41.55	8	20.87
						59.41	12	37.28	55.10	8	33.04
440	90	0.437	0.168	0.239	0.254	64.58	20	42.99	46.93	8	25.74
						60.28	12	38.11	55.97	8	33.87
430	100	0.436	0.121	0.225	0.237	62.42	16	40.82	49.30	8	27.88
						60.28	12	38.12	58.12	10	35.83
425	110	0.436	0.085	0.223	0.228	60.27	12	38.11	51.44	8	29.81
						59.18	12	37.13	59.18	12	37.13
330	120	0.422	0.057	0.214	0.216	59.85	12	37.93	54.47	8	32.71
						59.85	12	37.93	58.78	12	36.97
335	130	0.431	0.037	0.217	0.218	59.61	12	37.58	55.32	8	33.36
						59.61	12	37.58	59.61	12	37.58

Table F5.24(IV): Calc. $V_{meas} = ½ V_{max}(1+R^n)$; n = 1.9 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover
345	140	0.434	0.026	0.217	0.218	59.34	12	37.38	57.07	8	34.90
						59.43	12	37.38	59.43	12	37.38
350	150	0.434	0.018	0.213	0.217	59.85	12	37.77	57.68	10	35.46
						59.85	12	37.77	59.85	12	37.77
355	160	0.431	0.012	0.216	0.216	59.64	12	37.61	57.48	10	35.31
						59.64	12	37.61	59.64	12	37.61
400	170	0.431	0.007	0.212	0.216	59.20	12	37.21	58.12	10	35.89
						60.50	12	38.38	59.20	12	37.21
410	180	0.43	0.005	0.219	0.215	58.98	12	37.03	58.98	12	37.03
						58.98	12	37.03	58.98	12	37.03
415	190	0.432	0.002	0.211	0.216	58.32	10	36.05	58.32	10	36.05
						60.50	12	38.36	58.32	10	36.05
420	200	0.43	0.002	0.214	0.215	58.98	12	37.03	58.98	12	37.03
						60.05	12	38	58.98	12	37.03

Table F5.25(IV): Calc. $V_{meas} = ½ V_{max}(1+R^n)$; n = 2.0 12mm re-bar at 35mm cover

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover
255	60	0.481	0.41	0.411	0.416	60.71	16	38.70	$V_{max} < 2\ V_{min}$ 33.58	8	13.22
						60.71	16	38.70	54.45	8	31.99
450	70	0.454	0.32	0.328	0.337	71.25	20	48.76	$V_{max} < 2$ 37.67	8	17.21
						58.57	12	36.63	54.25	8	32.12
445	80	0.441	0.24	0.272	0.283	49.85	20	56.67	$V_{max} < 2$ 41.55	8	20.87
						59.41	12	37.28	55.10	8	33.04

Table F5.25(IV): Calc. $V_{meas} = ½\ V_{max}(1+R^{n})$; n = 2.0 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max}) / Width(V_{mine})	Size / Size	Cover / Cover	Width(V_{max}+V_{min}) / Width(Calc. V_{meas})	Size / Size	Cover / Cover
440	90	0.437	0.17	0.239	0.251	64.58	20	42.99	46.93	8	25.74
						60.28	12	38.11	57.04	8	34.83
430	100	0.436	0.12	0.225	0.235	62.42	16	40.82	49.30	8	27.88
						60.28	12	38.12	58.12	10	35.83
425	110	0.436	0.09	0.223	0.226	60.27	12	38.11	51.44	8	29.81
						59.18	12	37.13	59.18	12	37.13
330	120	0.422	0.06	0.214	0.215	59.85	12	37.93	54.47	8	32.71
						59.85	12	37.93	59.85	12	37.93
335	130	0.431	0.04	0.217	0.217	59.61	12	37.58	55.32	8	33.36
						59.61	12	37.58	59.61	12	37.58
345	140	0.434	0.03	0.217	0.218	59.43	12	37.38	57.07	8	34.90
						59.43	12	37.38	59.43	12	37.38
350	150	0.434	0.02	0.213	0.217	59.85	12	37.77	57.68	10	35.46
						59.85	12	37.77	59.85	12	37.77
355	160	0.431	0.01	0.216	0.216	59.64	12	37.61	57.48	10	35.31
						59.64	12	37.61	59.64	12	37.61
400	170	0.431	0.01	0.212	0.216	59.20	12	37.21	58.12	10	35.89
						60.50	12	38.38	59.20	12	37.21
410	180	0.430	0.01	0.219	0.215	58.98	12	37.03	58.98	12	37.03
						58.98	12	37.03	58.98	12	37.03
415	190	0.432	0	0.211	0.216	59.43	12	37.40	58.32	10	36.05
						60.50	12	38.36	58.32	10	36.05
420	200	0.430	0	0.214	0.215	58.98	12	37.03	58.98	12	37.03
						60.05	12	38.00	58.98	12	37.03

Experiment V

Table F5.26(V): Calc. $V_{meas} = ½ V_{max}(1+R^n)$; n = 1.7 — 20mm re-bar at various covers

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
300	80	0.709	0.413	0.455	0.496	79.44	20	53.44	41.10	8	17.92	35
						61.78	20	37.52	52.95	8	28.58	
305	80	0.479	0.305	0.332	0.351	79.22	20	55.59	41.55	8	20.42	$V_{max} < 2$ 40
						61.14	16	39.11	54.47	10	32.03	
307	80	0.329	0.225	0.243	0.251	81.79	20	60.25	41.98	8	22.86	45
						60.28	12	39.75	54.88	8	34.46	
319	90	0.713	0.304	0.410	0.440	69.94	20	44.86	46.27	8	22.53	35
						61.37	20	37.16	55.97	12	31.50	
321	90	0.479	0.231	0.288	0.304	83.95	20	59.84	46.94	8	25.26	40
						63.30	20	41.27	57.90	12	35.45	
323	90	0.324	0.176	0.212	0.216	90.84	69	64.48	46.30	8	26.82	45
						61.57	12	40.99	59.41	10	38.63	
331	100	0.628	0.211	0.335	0.362	67.38	20	43.32	49.94	8	26.51	35
						62.85	20	39.25	58.55	16	35.21	
335	100	0.423	0.163	0.248	0.253	72.54	20	50.35	50.80	8	29.40	40
						61.55	16	40.22	59.41	12	37.51	
339	100	0.288	0.127	0.179	0.180	79.65	20	59.17	49.50	8	30.35	45
						62.44	12	42.46	62.44	12	42.46	
350	110	0.684	0.152	0.347	0.368	62.88	20	38.77	54.04	8	29.74	35
						62.88	20	38.77	60.70	20	36.80	
355	120	0.685	0.110	0.345	0.357	62.00	20	37.96	55.52	10	31.06	35
						62.00	20	37.96	60.92	20	37.00	
410	130	0.673	0.080	0.333	0.345	62.87	20	38.85	56.40	12	32.21	35
						62.87	20	38.85	60.71	20	36.91	

Table F5.26(V): Calc. $V_{meas} = ½\,V_{max}(1+R^{n})$; n = 1.7 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
420	140	0.692	0.054	0.342	0.35	62.85	20	38.67	58.55	16	34.66	35
						62.85	20	38.67	61.78	20	37.71	
422	140	0.461	0.048	0.248	0.235	65.88	20	43.83	60.48	16	38.74	40
						61.57	16	39.72	63.71	20	41.88	
425	140	0.313	0.04	0.177	0.161	68.02	20	48.18	61.57	12	41.19	45
						61.57	12	41.19	65.88	20	46.26	
430	150	0.691	0.037	0.342	0.348	61.57	20	37.53	59.41	16	35.44	35
						62.85	20	38.68	61.57	20	37.53	
435	200	0.692	0.006	0.348	0.346	61.57	20	37.52	61.57	20	37.52	35
						61.57	20	37.52	61.57	20	37.52	

Table F5.27(V): Calc. $V_{meas} = ½\,V_{max}(1+R^{n})$; n = 1.8 20mm re-bar at various covers

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
300	80	0.709	0.413	0.455	0.489	79.44	20	53.44	41.10	8	17.92	35
						61.78	20	37.52	55.32	10	30.71	
305	80	0.479	0.305	0.332	0.346	82.45	20	58.49	41.55	8	20.42	$V_{max} < 2$ 40
						61.14	16	39.11	56.82	10	34.15	
307	80	0.329	0.225	0.243	0.248	81.79	20	60.25	41.98	8	22.86	45
						60.28	12	39.75	57.05	8	36.41	
319	90	0.713	0.304	0.410	0.433	69.94	20	44.86	46.27	8	22.53	35
						61.37	20	37.16	57.04	12	32.47	
321	90	0.479	0.231	0.288	0.304	83.95	20	59.84	46.94	8	25.26	40
						63.30	20	41.27	57.90	12	35.45	
323	90	0.324	0.176	0.212	0.216	91.07	20	73.51	46.30	8	26.82	45
						61.57	12	40.99	60.50	12	40.03	

Table F5.27(V): Calc. V_{meas} = ½ $V_{max}(1+R^n)$; n = 1.8 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
331	100	0.628	0.211	0.335	0.357	67.38	20	43.32	49.94	8	26.51	35
						62.85	20	39.25	59.64	16	36.19	
335	100	0.423	0.163	0.248	0.249	72.54	20	50.35	50.80	8	29.40	40
						61.55	16	40.22	61.55	16	40.22	
339	100	0.288	0.127	0.179	0.177	79.65	20	59.17	49.50	8	30.35	45
						62.44	12	42.46	62.44	12	42.46	
350	110	0.684	0.152	0.347	0.365	62.88	20	38.77	54.04	8	29.74	35
						62.88	20	38.77	60.70	20	36.80	
355	120	0.685	0.110	0.345	0.355	62.00	20	37.96	55.52	10	31.06	35
						62.00	20	37.96	60.92	20	37.00	
410	130	0.673	0.080	0.333	0.344	62.87	20	38.85	56.40	12	32.21	35
						62.87	20	38.85	60.71	20	36.91	
420	140	0.692	0.054	0.342	0.350	62.85	20	38.67	58.55	16	34.66	35
						62.85	20	38.67	61.78	20	37.71	
422	140	0.461	0.048	0.248	0.234	65.88	20	43.83	60.48	16	38.74	40
						61.57	16	39.72	64.80	20	42.86	
425	140	0.313	0.040	0.177	0.161	68.02	20	48.18	61.57	12	41.19	45
						61.57	12	41.19	66.95	20	47.22	
430	150	0.691	0.037	0.342	0.347	61.57	20	37.53	59.41	16	35.44	35
						62.85	20	38.68	61.57	20	37.53	
435	200	0.692	0.006	0.348	0.346	61.57	20	37.52	61.57	20	37.52	35
						61.57	20	37.52	61.57	20	37.52	

Table F5.28(V): Calc. V_{meas} = ½ $V_{max}(1+R^{n})$; n = 1.9 20mm re-bar at various covers

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
300	80	0.709	0.41	0.455	0.481	79.44	20	53.44	41.10	8	17.92	35
						61.78	20	37.52	55.32	10	30.71	
305	80	0.479	0.31	0.332	0.341	81.37	20	57.52	41.55	8	20.42	V_{max} < 2 40
						61.14	16	39.11	56.82	10	34.15	
307	80	0.329	0.23	0.243	0.245	81.79	20	60.25	41.98	8	22.86	45
						60.28	12	39.75	58.12	8	37.37	
319	90	0.713	0.30	0.41	0.427	69.94	20	44.86	46.27	8	22.53	35
						61.37	20	37.16	58.11	16	34.09	
321	90	0.479	0.23	0.288	0.295	83.95	20	59.84	46.94	8	25.26	40
						63.30	20	41.27	60.05	12	37.39	
323	90	0.324	0.18	0.212	0.210	96.44	20	73.51	46.30	8	26.82	45
						61.57	12	40.99	61.57	12	40.99	
331	100	0.628	0.21	0.335	0.353	67.38	20	43.32	49.94	8	26.51	35
						62.85	20	39.25	60.71	16	37.15	
335	100	0.423	0.16	0.248	0.246	72.54	20	50.35	50.80	8	29.40	40
						61.55	16	40.22	61.55	16	40.22	
339	100	0.288	0.13	0.179	0.175	79.65	20	59.17	49.50	8	30.35	45
						62.44	12	42.46	64.58	16	45.27	
350	110	0.684	0.15	0.347	0.362	62.88	20	38.77	54.04	8	29.74	35
						62.88	20	38.77	60.70	20	36.80	
355	120	0.685	0.11	0.345	0.352	62	20	37.96	55.52	10	31.06	35
						62	20	37.96	62.00	20	37.96	
410	130	0.673	0.08	0.333	0.342	62.87	20	38.85	56.40	12	32.21	35
						62.87	20	38.85	60.71	20	36.91	

Table F5.28(V): Calc. $V_{meas} = ½\ V_{max}(1+R^{n})$; n = 1.9 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
420	140	0.692	0.05	0.342	0.349	62.85	20	38.67	58.55	16	34.66	35
						62.85	20	38.67	61.78	20	37.71	
422	140	0.461	0.05	0.248	0.234	65.88	20	43.83	60.48	16	38.74	40
						61.57	16	39.72	64.80	20	42.86	
425	140	0.313	0.04	0.177	0.160	68.02	20	48.18	61.57	12	41.19	45
						61.57	12	41.19	68.02	20	48.18	
430	150	0.691	0.04	0.342	0.347	61.57	20	37.53	59.41	16	35.44	35
						62.85	20	38.68	61.57	20	37.53	
435	200	0.692	0.01	0.348	0.346	61.57	20	37.52	61.57	20	37.52	35
						61.57	20	37.52	61.57	20	37.52	

Table F5.29(V): Calc. $V_{meas} = ½\ V_{max}(1+R^{n})$; n = 2.0 20mm re-bar at various covers

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
300	80	0.709	0.413	0.455	0.475	77.07	20	51.31	41.10	8	17.92	35
						61.78	20	37.52	57.48	12	32.90	
305	80	0.479	0.305	0.332	0.336	84.61	20	60.43	41.55	8	20.42	$V_{max} < 2$ 40
						61.14	16	39.11	58.98	12	36.42	
307	80	0.329	0.225	0.243	0.241	83.74	20	62.00	41.98	8	22.86	45
						60.28	12	39.75	61.35	12	40.71	
319	90	0.713	0.304	0.410	0.421	69.94	20	44.86	46.27	8	22.53	35
						61.37	20	37.16	59.20	16	35.06	
321	90	0.479	0.231	0.288	0.295	83.95	20	59.84	46.94	8	25.26	40
						62.21	16	40.07	61.12	16	39.10	
323	90	0.324	0.176	0.212	0.210	92.14	20	69.64	46.30	8	26.82	45
						61.57	12	40.99	63.71	16	43.77	

Table F5.29(V): Calc. V_{meas} = ½ $V_{max}(1+R^{n})$; n = 2.0 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width(V_{max}+V_{min})	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
331	100	0.628	0.211	0.335	0.349	67.38	20	43.32	49.94	8	26.51	35
						62.85	20	39.25	60.71	16	37.15	
335	100	0.423	0.163	0.248	0.243	72.54	20	50.35	50.80	8	29.40	40
						61.55	16	40.22	62.64	16	41.19	
339	100	0.288	0.127	0.179	0.172	79.65	20	59.17	49.50	8	30.35	45
						62.44	12	42.46	64.58	16	45.27	
350	110	0.684	0.152	0.347	0.359	62.88	20	38.77	54.04	8	29.74	35
						62.88	20	38.77	60.7	20	36.80	
355	120	0.685	0.110	0.345	0.351	62	20	37.96	55.52	10	31.06	35
						62	20	37.96	60.7	20	37.96	
410	130	0.673	0.080	0.333	0.341	62.87	20	38.85	56.4	12	32.21	35
						62.87	20	38.85	61.8	20	37.89	
420	140	0.692	0.054	0.342	0.348	62.85	20	38.67	58.55	16	34.66	35
						62.85	20	38.67	61.78	20	37.71	
422	140	0.461	0.048	0.248	0.233	65.88	20	43.83	60.48	16	38.74	40
						61.57	16	39.72	64.80	20	42.86	
425	140	0.313	0.040	0.177	0.159	68.02	20	48.18	61.57	12	41.19	45
						61.57	12	41.19	68.02	20	48.18	
430	150	0.691	0.037	0.342	0.346	61.57	20	37.53	59.41	16	35.44	35
						62.85	20	38.68	61.57	20	37.53	
435	200	0.692	0.006	0.348	0.346	61.57	20	37.52	61.57	20	37.52	35
						61.57	20	37.52	61.57	20	37.52	

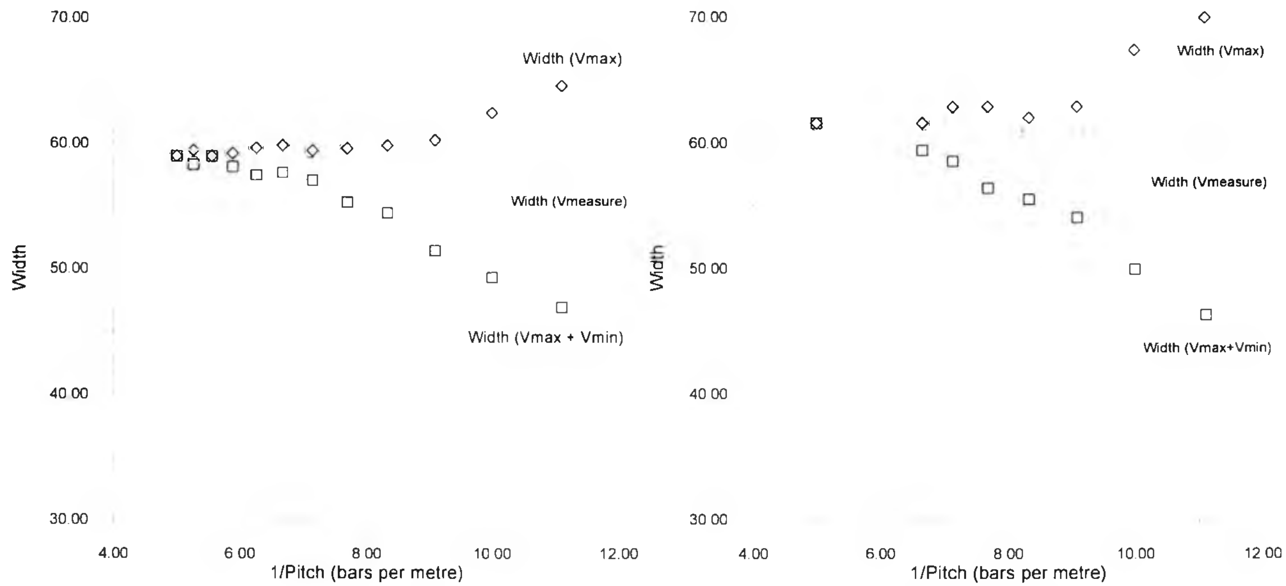
Table F5.30(V): Calc. $V_{meas} = ½ V_{max}(1+R^n)$; n = 2.1 20mm re-bar at various covers

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
300	80	0.709	0.413	0.455	0.468	79.44	20	53.44	41.10	8	17.92	35
						61.78	20	37.52	58.57	16	34.54	
305	80	0.479	0.305	0.332	0.332	81.37	20	57.52	41.55	8	20.42	V_{max} < 2 40
						61.14	16	39.11	61.14	16	39.11	
307	80	0.329	0.225	0.243	0.241	83.74	20	62.00	41.98	8	22.86	45
						60.28	12	39.75	61.35	12	40.71	
319	90	0.713	0.304	0.410	0.416	69.94	20	44.86	46.27	8	22.53	35
						61.37	20	37.16	60.28	16	36.04	
321	90	0.479	0.231	0.288	0.292	83.95	20	59.84	46.94	8	25.26	40
						63.3	16	41.27	62.21	16	40.07	
323	90	0.324	0.176	0.212	0.207	94.06	20	71.38	46.30	8	26.82	45
						61.57	12	40.99	63.71	16	43.77	
331	100	0.628	0.211	0.335	0.345	67.38	20	43.32	49.94	8	26.51	35
						62.85	20	39.25	60.71	16	37.15	
335	100	0.423	0.163	0.248	0.240	72.54	20	50.35	50.80	8	29.40	40
						61.55	16	40.22	63.71	16	42.16	
339	100	0.288	0.127	0.179	0.170	79.65	20	59.17	49.50	8	30.35	45
						62.44	12	42.46	66.72	20	47.55	
350	110	0.684	0.152	0.347	0.356	62.88	20	38.77	54.04	8	29.74	35
						62.88	20	38.77	60.70	20	36.80	
355	120	0.685	0.110	0.345	0.350	62.00	20	37.96	55.52	10	31.06	35
						62.00	20	37.96	62.00	20	37.96	
410	130	0.673	0.080	0.333	0.340	62.87	20	38.85	56.40	12	32.21	35
						62.87	20	38.85	62.87	20	38.85	

Table F5.30(V): Calc. $V_{meas} = ½ V_{max}(1+R^{n})$; n = 2.1 (Continued)

Filename	Pitch	V_{max}	V_{min}	$V_{measure}$	Calc. V_{meas}	Width(V_{max})	Size	Cover	Width($V_{max}+V_{min}$)	Size	Cover	Recorded Cover
						Width(V_{mine})	Size	Cover	Width(Calc. V_{meas})	Size	Cover	Recorded Cover
420	140	0.692	0.054	0.342	0.348	62.85	20	38.67	58.55	16	34.66	35
						62.85	20	38.67	62.85	20	38.67	
422	140	0.461	0.048	0.248	0.232	65.88	20	43.83	60.48	16	38.74	40
						61.57	16	39.72	64.80	20	42.86	
425	140	0.313	0.040	0.177	0.159	68.02	20	48.18	61.57	12	41.19	45
						61.57	12	41.19	68.02	20	48.18	
430	150	0.691	0.037	0.342	0.346	61.57	20	37.53	59.41	16	35.44	35
						62.85	20	38.68	61.57	20	37.53	
435	200	0.692	0.006	0.348	0.346	61.57	20	37.52	61.57	20	37.52	35
						61.57	20	37.52	61.57	20	37.52	

Graphical Analysis of Experiments IV and V
(From Tables IV & V)



(a) Plot for 12mm re-bars at 36mm cover (b) Plot for 20mm re-bars at 36mm cover

Figure F5.6 Plots of Width versus 1/Pitch (bars per metre) for 12mm and 20mm re-bars

Appendix F-5

Traverse Profile Raw Data Sample (1/ Hundreds)

Table F-5.1 Sample data of a traverse scan on a single re-bar

Distance	CM5	Distance	CM5	Distance	CM5	Distance	CM5
387.029	0.000	449.468	0.045	513.208	0.408	575.601	0.032
389.630	0.001	452.039	0.053	515.748	0.402	578.187	0.027
392.216	0.001	455.068	0.064	518.364	0.392	580.757	0.024
394.771	0.001	457.638	0.075	520.919	0.379	583.343	0.019
397.800	0.001	460.209	0.087	523.505	0.364	585.944	0.017
400.401	0.002	462.810	0.100	526.121	0.345	588.515	0.014
402.956	0.001	465.380	0.115	528.692	0.326	591.559	0.012
405.572	0.002	467.966	0.133	531.262	0.303	594.130	0.009
408.143	0.002	470.552	0.154	533.848	0.281	596.685	0.008
410.729	0.004	473.566	0.173	536.449	0.257	599.301	0.007
413.284	0.005	476.167	0.194	539.004	0.233	601.902	0.005
415.869	0.005	478.768	0.217	541.589	0.211	604.457	0.005
418.455	0.006	481.307	0.241	544.206	0.190	607.043	0.004
421.041	0.006	483.893	0.263	546.761	0.166	609.628	0.004
423.626	0.008	486.494	0.286	549.775	0.146	612.199	0.002
426.197	0.009	489.065	0.308	552.376	0.129	614.785	0.001
428.783	0.012	491.635	0.329	554.962	0.113	617.370	0.002
431.384	0.014	494.236	0.350	557.532	0.098	619.956	0.001
433.969	0.017	497.250	0.370	560.133	0.084	622.526	0.001
436.540	0.019	499.851	0.384	562.688	0.072	625.541	0.000
439.125	0.024	502.437	0.396	565.274	0.062	628.126	0.001
441.711	0.027	504.992	0.404	567.859	0.053	630.712	0.001
444.281	0.032	507.991	0.410	570.430	0.046	633.328	0.000
446.867	0.038	510.592	0.411	573.016	0.038		

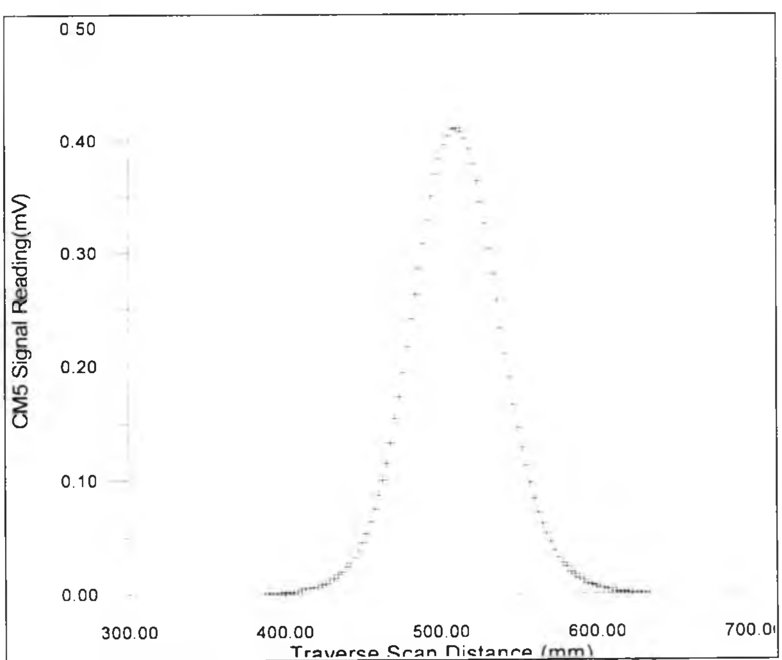


Figure F-5.1 Plot of the sample data of Table F-5.1

Appendix G

Construction Industry HMI Questionnaire Survey

G.1 Introduction

A questionnaire survey was conducted by mail in late 1994, to determine current HMI (Human-Machine Interface) activity in the construction industry. In the industry, the term HMI is commonly referred to as MMI (Man-Machine Interface), but a non-gender specific term, HMI will be used here. The questionnaire survey is divided into three parts; nature of work, robot identity and existing robot interface. The questionnaires were sent to relevant speakers of the ISARC'94 conference (Chamberlain, 1994). The survey consists of four answered questionnaires from Japan, two from Britain, one from the Netherlands, one from the US and one from the Czech Republic. The returned questionnaires are presented after the survey analysis, discussed next.

G.2 Analysis of Results

This survey is by no means comprehensive, as it would require a far greater number of questionnaire responses. However, the results do provide some indication to the current trends in HMI within the construction industry. Table G.1 provides a graphical summary of the results of the survey.

Referring to the results in Table G.1, a few points can be generalized about robots and HMI in the construction industry. Firstly, the high mobility figure is an indication of the importance of robot mobility in the construction industry. Secondly, both tele-operated systems and semi autonomous systems represent a large number of robot operations. Both these systems rely on operator participation. In a more recent survey, tele-operated systems were found to constitute two thirds of robot systems developed for the construction industry (Warszawski & Navon, 1995). Pre-programmed and fully autonomous systems, however, are less common. This should be to no surprise, as construction sites are often too complex for pre-programming, or total automation.

Table G.1 Summary Results of the HMI Questionnaire Survey

HMI Survey	No.	Bar Graph
Robot		
Development Status		
Incomplete 1st Prototype	5	
1st Working Prototype	4	
Advanced Prototype	1	
Commercially Available	3	
Mobility		
Static	2	
Re-locatable	2	
Fully Mobile	7	
Operation		
Pre-programmed	2	
Tele-operated	5	
Semi-autonomous	4	
Fully autonomous	2	
Interface		
Training Requirement		
0 - 3hrs	3	
3hrs - 3days	4	
3 days or more	0	
System Developer Only	2	
Type of User Interface		
Electro-Machanical	5	
Hybrid-System	2	
Software Interface Only	3	
Input Device		
Keyboard	9	
Touch Screen	1	
Buttons	4	
Mouse	2	
Knobs	1	
Switches	2	
VR Equipment	2	
Joystick	3	
Pendant	1	

It is difficult to conduct usability studies on different robots through a questionnaire survey. However, the questionnaire can provide an indication of usability through the measure of how long it takes to train to operate a robotic system. As mentioned, this is not an ideal indicator of usability, as some systems are far more complex to operate than others, hence requiring a longer training time. In the survey, training time on robotic systems were found to take no more than 3 days and almost half, no longer than 3 hours. The reply of 'system developer only', is not an implication of system complexity, but of an incomplete first prototype. The short training time found in the survey indicates awareness of system usability in the construction industry. Usability awareness can also be seen in the increase of papers at ISARC conferences (ISARC Proceedings, 1990-1995) with discussions on HMI/ MMI related issues.

In terms of the interface, electro-mechanical interfaces appear to be the most common. Again, the software interfaces only is an indication of an incomplete first prototype, where it is the norm. The keyboard is still the most popular input device. Its usage is often for text entry rather than in the manipulation of the robot itself. Next to it, buttons and joysticks are the most often encountered input devices. They are primarily used in the direct manipulation of robotic devices. It is also interesting to see that such recent technology as virtual reality is receiving some attention as a method of interfacing with robots. As for output devices are concerned, a monitor was prevalent in all systems surveyed.

Junichiro Maeda
Deputy General Manager Building
Technology Department
Technology Development Division
Shimizu Corporation
Seavans South 2-3 Shibaura 1-chome
Minato-ku
Tokyo 105-07
Japan

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware :	☐ Research	☑ Development	☐ Application
Software :	☐ Research	☑ Development	☐ Application

Part 2 : Robot Identity

1. Name of robot / project : *Automated Building Construction System*
2. Main function of robot : *Automation of high-rise building including material transportation, positioning, welding and plant lifting-up*
3. Producer of robot : ☐ In house ☑ External ☐ Both
   - 3.1 Name of contractor : *Mitsubishi Heavy Industry Co. Ltd.*
   - 3.2 Address of contractor : *Steel Construction Division, No. 5-1, Marunouchi 2-chome, Chiyodo-ku, 100 Tokyo, Japan*
4. Development status :
   - ☐ Incomplete first prototype
   - ☐ First working prototype
   - ☐ Advanced prototype
   - ☑ Commercially available robot
5. Number of degrees of freedom of the robot : ☐☐
6. Mobility : ☐ Static ☐ Re-locatable ☑ Fully mobile
7. Mode of operation : ☑ Pre-programmed ☐ Tele-operated ☐ Semi-autonomous ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   - ☐ 0 - 3 hrs training
   - ☑ 3 hrs - 3 days training
   - ☐ 3 days or more
   - ☐ system developer only
2. Type of user interface : ☐ Electro-mechanical ☑ Hybrid-system ☐ Software interface only
3. Operator input devices :

☑ Keyboard	☐ Mouse	☐ Light pen
☐ Touch screen	☐ Track ball	☐ Joy stick
☐ Digitizer / tablet	☐ Knobs	☐ Slider bars
☑ Buttons	☑ Switches	☐ Pendant
☐ Speech	☐ VR equipments	☐ Others (Please specify below)

4. Operator output device :

☑ Monitor / screens	☑ LEDs	☐ Dials
☐ Charts / graphs	☑ Text	

5. Are system enhancements envisioned : ☑ Yes ☐ No

Shigeru Sakamoto
Manager Construction Technology
Development Department
Sanken Building
Taisei Corporation
3-25-1 Hyakunin-cho
Shinjuku-ku
Tokyo 169
Japan

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware : ☐ Research ☑ Development ☑ Application

Software : ☐ Research ☑ Development ☑ Application

Part 2 : Robot Identity

1. Name of robot / project : *Various kinds of robot for construction*
2. Main function of robot : *Painting, Diagnostics etc. (about 20 kinds)*
3. Producer of robot : ☐ In house ☐ External ☑ Both
   - 3.1 Name of contractor : *Building owner, Japan Broadcasting Corp.*
   - 3.2 Address of contractor : *Mitsurulishi Heavy Industry Co. etc.*
4. Development status :
   - ☑ Incomplete first prototype ☑ First working prototype
   - ☑ Advanced prototype ☑ Commercially available robot
5. Number of degrees of freedom of the robot : 5~6
6. Mobility : ☐ Static ☑ Re-locatable ☑ Fully mobile
7. Mode of operation : ☑ Pre-programmed ☑ Tele-operated ☑ Semi-autonomous ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   - ☐ 0 - 3 hrs training ☑ 3 hrs - 3 days training
   - ☐ 3 days or more ☐ system developer only
2. Type of user interface :
   - ☑ Electro-mechanical ☑ Hybrid-system ☐ Software interface only
3. Operator input devices :
   - ☑ Keyboard ☐ Mouse ☐ Light pen
   - ☐ Touch screen ☐ Track ball ☑ Joy stick
   - ☐ Digitizer / tablet ☑ Knobs ☐ Slider bars
   - ☑ Buttons ☑ Switches ☑ Pendant
   - ☐ Speech ☑ VR equipments ☐ Others (Please specify below)
4. Operator output device :
   - ☑ Monitor / screens ☐ LEDs ☑ Dials
   - ☐ Charts / graphs ☑ Text
5. Are system enhancements envisioned : ☑ Yes ☐ No

Masahiko Minamoto
Fujita Corporation (Ichiken)
2-17 Kandasude-cho
Chiyoda-ku
Tokyo 101
Japan

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware : ☐ Research ☑ Development ☐ Application

Software : ☐ Research ☑ Development ☐ Application

Part 2 : Robot Identity

1. Name of robot / project : Tele-earthwork Project
2. Main function of robot : Remote Control
3. Producer of robot : ☐ In house ☑ External ☐ Both
   - 3.1 Name of contractor :
   - 3.2 Address of contractor :
4. Development status :
   - ☐ Incomplete first prototype
   - ☐ First working prototype
   - ☐ Advanced prototype
   - ☑ Commercially available robot
5. Number of degrees of freedom of the robot :
6. Mobility : ☐ Static ☐ Re-locatable ☑ Fully mobile
7. Mode of operation :
   - ☐ Pre-programmed
   - ☑ Tele-operated
   - ☐ Semi-autonomous
   - ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   - ☑ 0 - 3 hrs training
   - ☐ 3 hrs - 3 days training
   - ☐ 3 days or more
   - ☐ system developer only
2. Type of user interface :
   - ☑ Electro-mechanical ☐ Hybrid-system ☐ Software interface only
3. Operator input devices :
   - ☐ Keyboard ☐ Mouse ☐ Light pen
   - ☐ Touch screen ☐ Track ball ☑ Joy stick
   - ☐ Digitizer / tablet ☐ Knobs ☐ Slider bars
   - ☑ Buttons ☐ Switches ☐ Pendant
   - ☐ Speech ☑ VR equipments ☐ Others (Please specify below)
4. Operator output device :
   - ☑ Monitor / screens ☐ LEDs ☐ Dials
   - ☐ Charts / graphs ☐ Text
5. Are system enhancements envisioned : ☑ Yes ☐ No

Yasunori Abe
Researcher
Researcher and Development Center
Shinryo Corporation
41 Wadal
Tsukuba
Ibaraki 300-42
Japan

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate.

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware : ☑ Research ☐ Development ☐ Application
Software : ☑ Research ☐ Development ☐ Application

Part 2 : Robot Identity

1. Name of robot / project : *Air Condition Equipment Inspection Robot*
2. Main function of robot : *Image processing, Autonomous mobility*
3. Producer of robot : ☐ In house ☐ External ☑ Both
   3.1 Name of contractor : *Shinryo Corp.*
   3.2 Address of contractor :
4. Development status :
   ☑ Incomplete first prototype ☐ First working prototype
   ☐ Advanced prototype ☐ Commercially available robot
5. Number of degrees of freedom of the robot : 3
6. Mobility : ☐ Static ☐ Re-locatable ☑ Fully mobile
7. Mode of operation : ☐ Pre-programmed ☐ Tele-operated ☑ Semi-autonomous ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   ☐ 0 - 3 hrs training ☐ 3 hrs - 3 days training
   ☐ 3 days or more ☑ system developer only
2. Type of user interface :
   ☑ Electro-mechanical ☐ Hybrid-system ☐ Software interface only
3. Operator input devices :
   ☑ Keyboard ☐ Mouse ☐ Light pen
   ☑ Touch screen ☐ Track ball ☐ Joy stick
   ☐ Digitizer / tablet ☐ Knobs ☐ Slider bars
   ☐ Buttons ☐ Switches ☐ Pendant
   ☐ Speech ☐ VR equipments ☐ Others (Please specify below)
4. Operator output device :
   ☑ Monitor / screens ☐ LEDs ☐ Dials
   ☐ Charts / graphs ☐ Text
5. Are system enhancements envisioned : ☑ Yes ☐ No

Prof. Matthew M. Cusack
Faculty of the Built Environment
University of West of England
Bristol
Frenchay Campus
Coldharbour Lane
Bristol BS16 1QY
U.K.

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware :	☑ Research	☑ Development	☐ Application
Software :	☑ Research	☑ Development	☐ Application

Part 2 : Robot Identity

1. Name of robot / project : *Wall Climbing Robot*
2. Main function of robot : *For inspection and maintenance of buildings*
3. Producer of robot : ☑ In house ☐ External ☐ Both
   - 3.1 Name of contractor :
   - 3.2 Address of contractor :
4. Development status :
   - ☐ Incomplete first prototype
   - ☑ First working prototype
   - ☐ Advanced prototype
   - ☐ Commercially available robot
5. Number of degrees of freedom of the robot : 5
6. Mobility : ☐ Static ☐ Re-locatable ☑ Fully mobile
7. Mode of operation :
   - ☐ Pre-programmed
   - ☑ Tele-operated
   - ☐ Semi-autonomous
   - ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   - ☑ 0 - 3 hrs training
   - ☐ 3 hrs - 3 days training
   - ☐ 3 days or more
   - ☐ system developer only
2. Type of user interface :
   - ☑ Electro-mechanical
   - ☐ Hybrid-system
   - ☐ Software interface only
3. Operator input devices :

☑ Keyboard	☐ Mouse	☐ Light pen
☐ Touch screen	☐ Track ball	☐ Joy stick
☐ Digitizer / tablet	☐ Knobs	☐ Slider bars
☐ Buttons	☐ Switches	☐ Pendant
☐ Speech	☐ VR equipments	☐ Others (Please specify below)

4. Operator output device :

☑ Monitor / screens	☐ LEDs	☑ Dials
☑ Charts / graphs	☐ Text	

5. Are system enhancements envisioned : ☑ Yes ☐ No

Construction Robotics Centre
Civil Engineering Department
City University
Northampton Square
London
EC1V 0HB
U.K.

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware :	☑ Research	☑ Development	☐ Application
Software :	☑ Research	☑ Development	☐ Application

Part 2 : Robot Identity

1. Name of robot / project : *CURIO & Wall Building Robot*
2. Main function of robot : *Inspection & Wall building Robot*
3. Producer of robot : ☐ In house ☐ External ☑ Both
   - 3.1 Name of contractor : *CROCUS*
   - 3.2 Address of contractor :
4. Development status :
   - ☑ Incomplete first prototype
   - ☐ First working prototype
   - ☐ Advanced prototype
   - ☑ Commercially available robot
5. Number of degrees of freedom of the robot : 5
6. Mobility : ☑ Static ☐ Re-locatable ☑ Fully mobile
7. Mode of operation :
   - ☐ Pre-programmed
   - ☑ Tele-operated
   - ☐ Semi-autonomous
   - ☑ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   - ☑ 0 - 3 hrs training
   - ☐ 3 hrs - 3 days training
   - ☐ 3 days or more
   - ☐ system developer only
2. Type of user interface :
   - ☐ Electro-mechanical ☐ Hybrid-system ☑ Software interface only
3. Operator input devices :

☑ Keyboard	☑ Mouse	☐ Light pen
☐ Touch screen	☐ Track ball	☐ Joy stick
☐ Digitizer / tablet	☐ Knobs	☐ Slider bars
☐ Buttons	☐ Switches	☐ Pendant
☐ Speech	☐ VR equipments	☐ Others (Please specify below)

4. Operator output device :

☑ Monitor / screens	☑ LEDs	☐ Dials
☑ Charts / graphs	☑ Text	

5. Are system enhancements envisioned : ☑ Yes ☐ No

Ronald Krom
Department of Computer Intregrated Construction
TNO Building and Construction Research
Lange Kleiweg 5
Rijswijk
P.O. Box 49
Delft 2600 AA
The Netherlands

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware : ☐ Research ☐ Development ☐ Application
Software : ☑ Research ☐ Development ☐ Application

Part 2 : Robot Identity

1. Name of robot / project : *Intelligent Task Level Instruction for Drilling Robot*
2. Main function of robot : *Drilling Robot*
3. Producer of robot : ☑ In house ☐ External ☐ Both
   3.1 Name of contractor : ______
   3.2 Address of contractor : ______
4. Development status :
   ☑ Incomplete first prototype ☐ First working prototype
   ☐ Advanced prototype ☑ Commercially available robot
5. Number of degrees of freedom of the robot : 3
6. Mobility : ☐ Static ☐ Re-locatable ☑ Fully mobile
7. Mode of operation : ☐ Pre-programmed ☐ Tele-operated ☐ Semi-autonomous ☑ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   ☐ 0 - 3 hrs training ☑ 3 hrs - 3 days training
   ☐ 3 days or more ☐ system developer only
2. Type of user interface :
   ☐ Electro-mechanical ☐ Hybrid-system ☑ Software interface only
3. Operator input devices :
   ☑ Keyboard ☑ Mouse ☐ Light pen
   ☐ Touch screen ☐ Track ball ☐ Joy stick
   ☐ Digitizer / tablet ☐ Knobs ☐ Slider bars
   ☐ Buttons ☐ Switches ☐ Pendant
   ☐ Speech ☐ VR equipments ☐ Others (Please specify below)
   ______
4. Operator output device :
   ☑ Monitor / screens ☐ LEDs ☐ Dials
   ☐ Charts / graphs ☐ Text
5. Are system enhancements envisioned : ☑ Yes ☐ No

William R. Bath
Chief Engineer
SONSUB Environmental Services
10905 Metronome
Houston TX 77043-2202
U.S.A.

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware : ☐ Research ☐ Development ☑ Application

Software : ☐ Research ☐ Development ☑ Application

Part 2 : Robot Identity

1. Name of robot / project : *PIT 9 - Retrieval System*
2. Main function of robot : *Excavate, Retrieve and Process of Tru Hazardous Waste*
3. Producer of robot : ☑ In house ☐ External ☐ Both
   - 3.1 Name of contractor : ______
   - 3.2 Address of contractor : ______
4. Development status :
   - ☐ Incomplete first prototype
   - ☑ First working prototype
   - ☐ Advanced prototype
   - ☐ Commercially available robot
5. Number of degrees of freedom of the robot : 3-5 *Depending on each*
6. Mobility : ☐ Static ☑ Re-locatable ☐ Fully mobile
7. Mode of operation :
   - ☐ Pre-programmed
   - ☑ Tele-operated
   - ☐ Semi-autonomous
   - ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :
   - ☐ 0 - 3 hrs training
   - ☑ 3 hrs - 3 days training
   - ☐ 3 days or more
   - ☐ system developer only
2. Type of user interface :
   ☐ Electro-mechanical ☐ Hybrid-system ☑ Software interface only
3. Operator input devices :
   - ☑ Keyboard ☐ Mouse ☐ Light pen
   - ☐ Touch screen ☐ Track ball ☑ Joy stick
   - ☐ Digitizer / tablet ☐ Knobs ☐ Slider bars
   - ☑ Buttons ☐ Switches ☐ Pendant
   - ☐ Speech ☐ VR equipments ☐ Others (Please specify below)

   ______
4. Operator output device :
   - ☑ Monitor / screens ☐ LEDs ☐ Dials
   - ☐ Charts / graphs ☐ Text
5. Are system enhancements envisioned : ☑ Yes ☐ No

Z. Kolibal
Technical University of Bmo
Technicka 2
BRNO 61669
Czech Republic

MAN-MACHINE INTERFACE STUDY

Please tick and answer the following questions where appropriate:

Part 1 : Nature of work

1. Which of the following are you involved in :

Robot hardware : ☐ Research ☑ Development ☐ Application

Software : ☐ Research ☑ Development ☐ Application

Part 2 : Robot Identity

1. Name of robot / project : Cartesian Robot TRXM-20
2. Main function of robot : Manipulator
3. Producer of robot : ☐ In house ☐ External ☑ Both

   3.1 Name of contractor : Vúzkuruna Restor Stavebuich Tímot

   3.2 Address of contractor : Hneukovkeko 65
   CZ-61700 Brno
   Czech Republic

4. Development status :

   ☐ Incomplete first prototype ☑ First working prototype

   ☐ Advanced prototype ☐ Commercially available robot

5. Number of degrees of freedom of the robot : 3
6. Mobility : ☑ Static ☐ Re-locatable ☐ Fully mobile
7. Mode of operation : ☐ Pre-programmed ☐ Tele-operated ☑ Semi-autonomous ☐ Fully autonomous

Part 3 : Existing robot interface

1. Operator qualification / skill requirement :

   ☐ 0 - 3 hrs training ☑ 3 hrs - 3 days training

   ☐ 3 days or more ☐ system developer only

2. Type of user interface :

   ☑ Electro-mechanical ☐ Hybrid-system ☐ Software interface only

3. Operator input devices :

   ☑ Keyboard ☐ Mouse ☐ Light pen

   ☐ Touch screen ☐ Track ball ☐ Joy stick

   ☐ Digitizer / tablet ☐ Knobs ☐ Slider bars

   ☐ Buttons ☐ Switches ☐ Pendant

   ☐ Speech ☐ VR equipments ☐ Others (Please specify below)

4. Operator output device :

   ☑ Monitor / screens ☐ LEDs ☐ Dials

   ☐ Charts / graphs ☐ Text

5. Are system enhancements envisioned : ☑ Yes ☐ No

Chamberlain, D.A. (Ed., 1994). Automation and Robotics in Construction XI. Proceedings of the 11th International Symposium on Automation and Robotics in Construction (ISARC).

Warszawski, A. & Navon, R. (1995). Survey of Building Robots. Automation and Robotics in Construction XIII. Proceedings of the 13th International Symposium on Automation and Robotics in Construction (ISARC).

Appendix H

CURIO HMI Survey

H.1 Introduction

A survey was conducted for the HMI control panels designed in Chapter 11, to determine user preferences between them. Description of the survey is covered herein, and conclusions provided. All the candidates surveyed have an engineering, or technical background.

H.2 Survey Objectives

The survey was conducted informally, on a one to one basis. The following three pages depict the HMI illustrations, that were included in the survey. With the first six (Fig. A to Fig. F), the objective was to determine the preferred Z and Stop button orientations. Figure G was compared to Figure H to determine if candidates preferred the 3-D perspective layout to the more conventional 2-D layout. Figures H and I were used to determine if users preferred lines through the various motion axes. Finally, Figures J and K were compared, to determine if candidates favored the third prototype control panel (motion icon) to the second 3-D perspective panel.

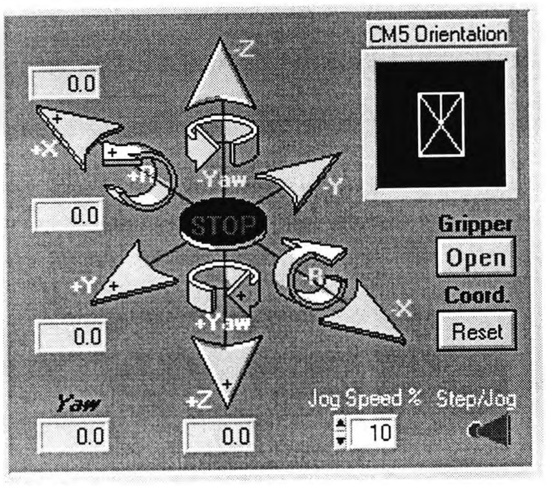


Fig. A

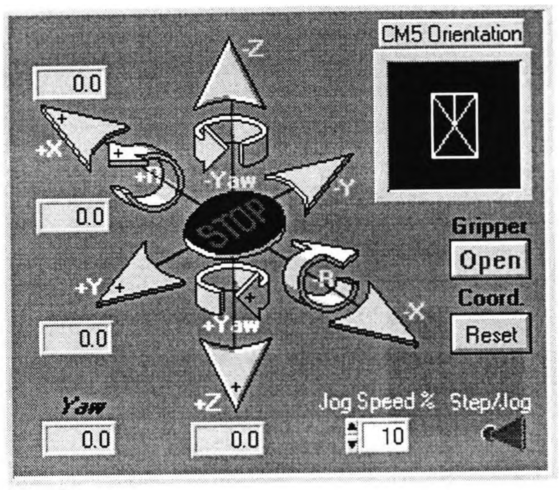


Fig. B

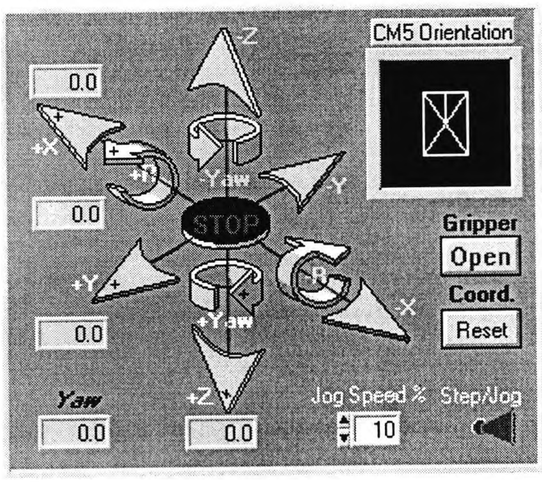


Fig. C

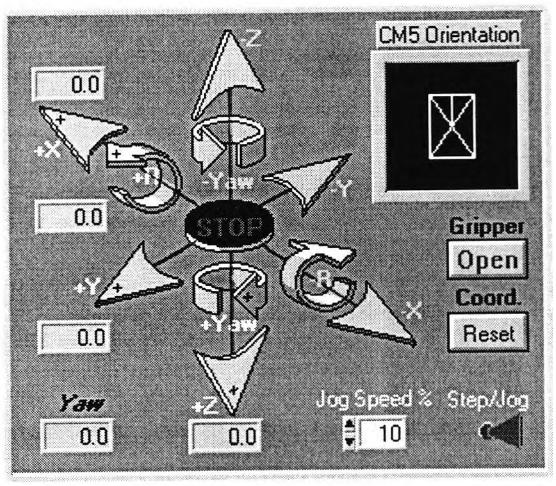


Fig. D

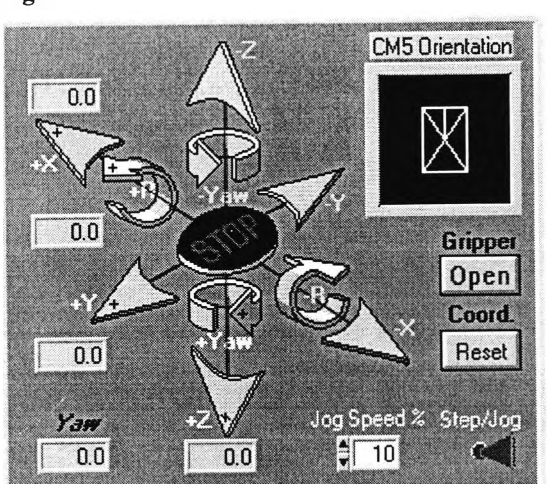


Fig. E

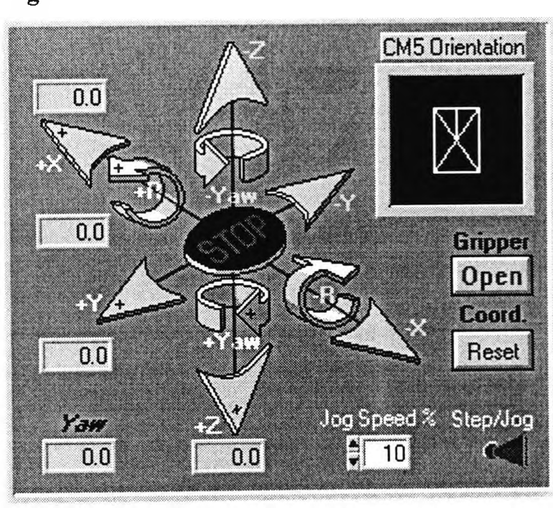
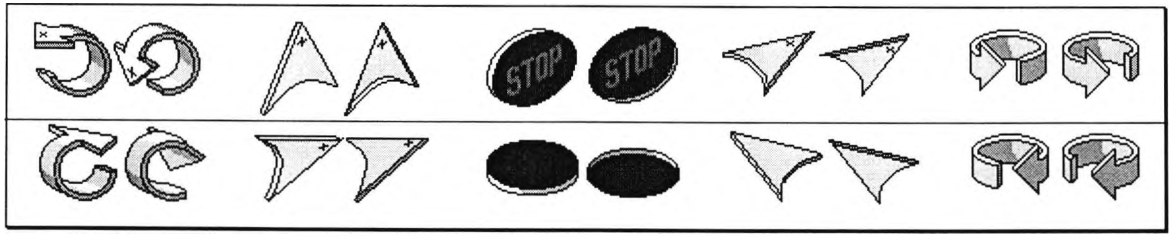


Fig. F



Animated sequences of some the 3-D buttons

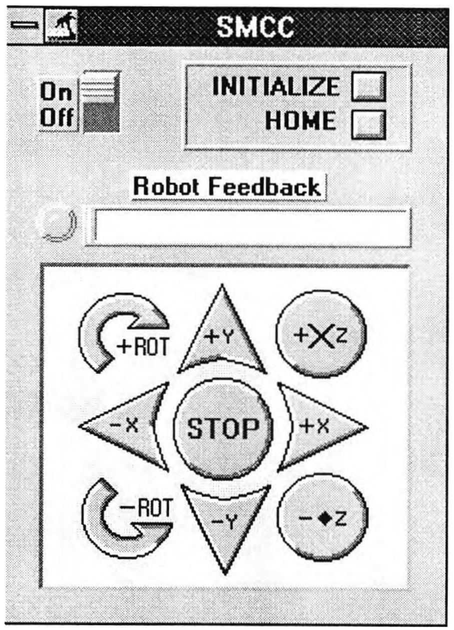


Fig. G [2-D layout]

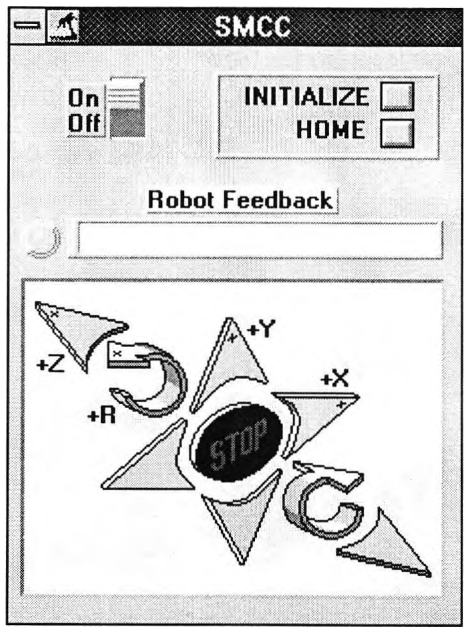


Fig. H [3-D layout]

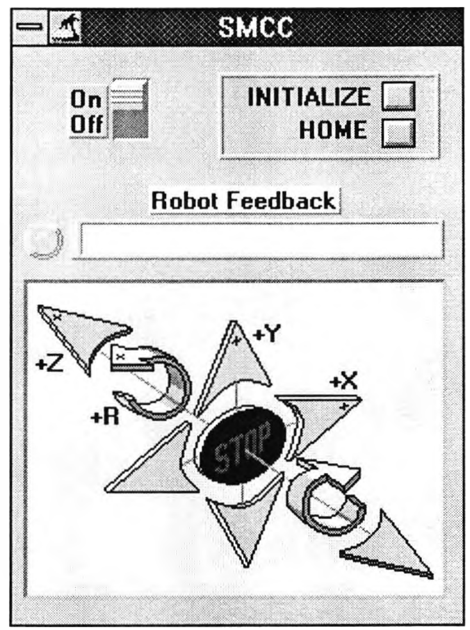


Fig. I [3-D layout with axial lines]

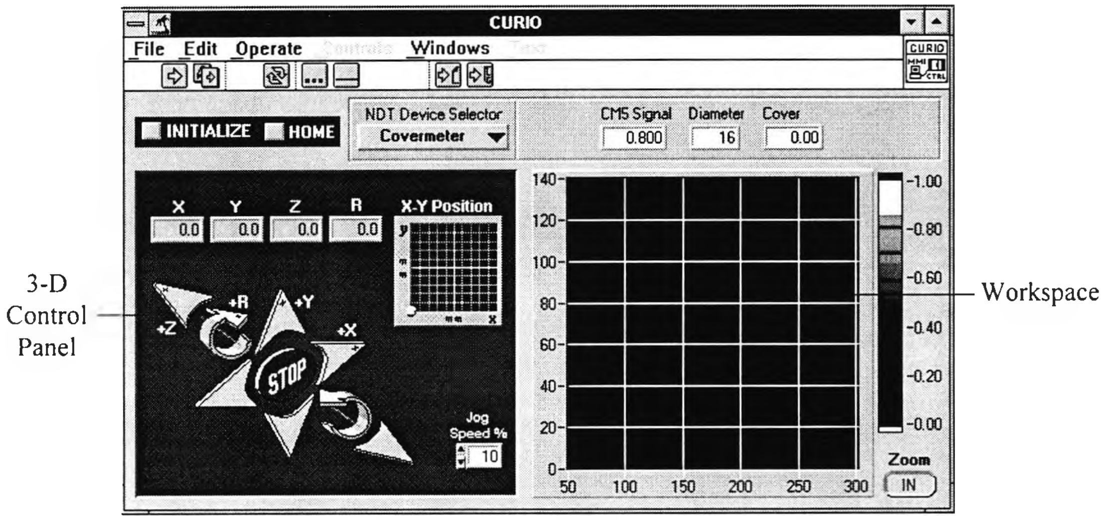


Fig. J CURIO prototype HMI control panel

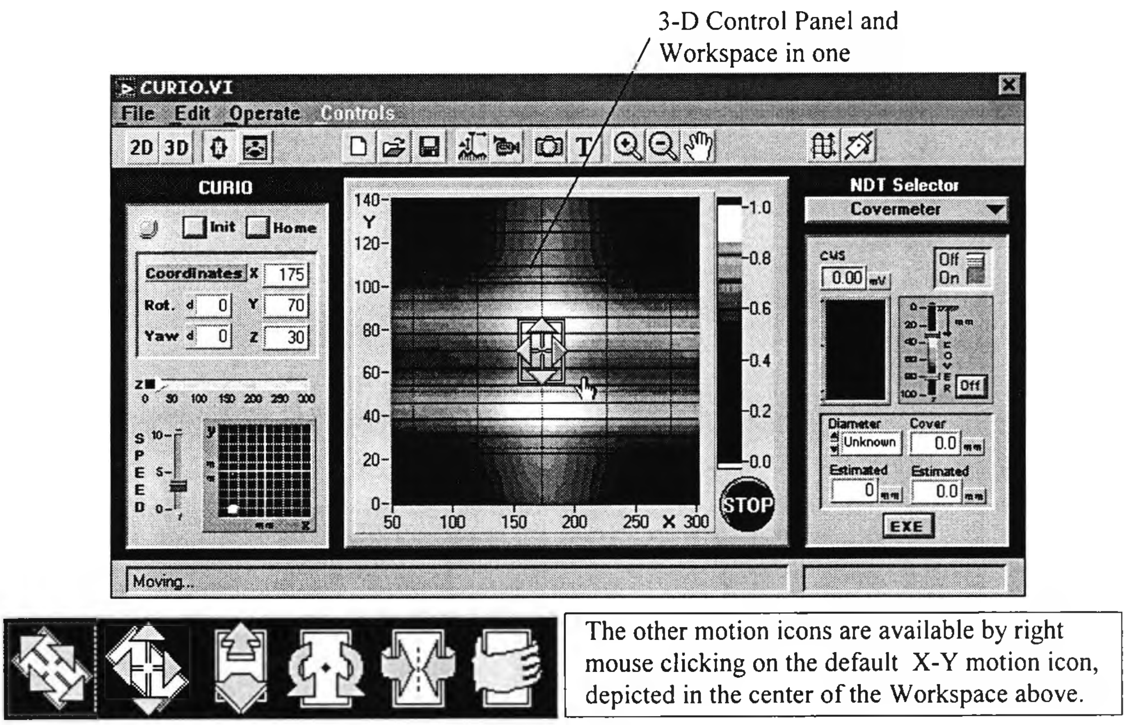


Fig. K CURIO prototype HMI control panel (Note X and Y motions are most frequently used during an inspection process)

Table H1: CURIO HMI Preferences Survey

Candidate No.	Experience	Gender	L or R handed	A	B	C	D	E	F	G	H	H	I	J	K	Comments
1	Extensive	F	R	3	2		1			1			1		1	Prefers simpler Z button. Prefers axis lines, not necessarily for X & Y.
2	Extensive	F	R	3	2		1			1			1		1	Prefers simpler Z button.
3	Familiar	M	R			1		2	3		1	1			1	Prefers angled Stop button.
4	Familiar	M	R	2	3				1		1		1		1	Prefers simpler Z and simpler Stop button.
5	Familiar	M	R	3			2		1		1	1			1	Prefers simpler Stop.
6	Extensive	M	R	1			2		3		1		1		1	Prefers correct perspective of F and simplicity of A.
7	Extensive	M	R		1			3	2		1		1			Prefers correct perspective and simplicity of Z button.
8	Extensive	M	R		1		2		3		1	1			1	Prefers large perspective Stop button.
9	Extensive	M	L & R			1		2	3	1			1	1		Prefers correct perspective.
10	Extensive	M	L	1		3	2				1	1			1	Prefers Z button in X-axis plane. Prefers axis lines, not necessarily for X & Y.
11	Extensive	M	L	1	3			2			1		1		1	Prefers simple Z button and correct perspective of E.
12	Extensive	M	L		3			1	2		1		1		1	Prefers large perspective Stop button.
Total Rating				**14**	**15**	**5**	**10**	**10**	**18**	**3**	**9**	**4**	**8**	**1**	**11**	

H.3 Conclusion

A few conclusions can be drawn from the total comparison ratings in Table H1. They are listed as follows:

1. Males generally prefer the 3-D perspective layout of Figure H, to the simpler 2-D layout of Figure G.
2. Females, the direct opposite of the above.
3. Right handed candidates generally prefer the Z buttons facing the right.
4. Left handed candidates generally prefer the Z buttons facing the left.
5. Candidates prefer Figures E and F, to Figures C and D because the Stop buttons are more perspectively correct than the latter two. More candidates prefer Figure F because of point 3 above, and because more of the surveyed candidates are right handed.
6. Even though most candidates favor the Stop perspective due to point 5 above, Figures A and B are of equal preference. The equal preference of A here, is probably due to the orientation of the Z buttons in the figure, which makes the Stop button appear perspectively correct.
7. Finally, there is an overwhelming preference for the motion control panel of Figure K, to Figure J.

References

Albers, J. (1963). Interaction of Color. New Haven, CT: Yale University Press.

Albert, A.E. (1982). The Effect of Graphic Input Devices on Performance in a Cursor Positioning Task. Proceedings on Human Factors Society. 26th Annual Meting. Pp. 54-58.

Alldred, J.; Chua, J.; Chamberlain, D. (1995), Determination of Reinforcing Bar Diameter and Cover by Analysing Traverse Profiles from a Cover Meter. International Symposium NDT in Civil Engineering, Vol. 1. Pp. 721-727.

Alldred, J.C. (1993) Lecture Notes for ACT Course: NDT - "Electronic Covermeters".

Alldred, J.C. (1993). An Improved Method for Measuring Reinforcing Bars of Unknown Diameter in Concrete using a Cover Meter. Conference Proceedings. Non-Destructive Testing in Civil Engineering. Vol.2.

Alldred, J.C. (1993). Quantifying the Losses in cover-meter accuracy due to Congestion of Reinforcement. Structural Faults & Repair.

Alldred, J.C. (1995). Improvements to the Orthogonal Method for Determining Reinforcing Bar Diameter using a Cover Meter. Structural Faults & Repairs.

Alldred, J.C. CM5 CoverMaster User Manual. Protovale (Oxford) Ltd.

Apple Computer (1987). Human Interface Guidelines: The Apple Desktop Interface. Addison Wesley Publishing Company, Inc. Reading, MA.

Arend, U., Muthig, K.P. & Wandmacher, J. (1987). Evidence for global feature superiority in menu selection by icons, Behaviour and Information Technology, 6. Pp. 411-426.

Arnheim, R. (1974). Art and Visual Perception. A Psychology of the Creative Eye, University of California Press, Berkeley, Calif.

Atkinson, J.W., & Shiffrin, R.M. (1968). Human memory: A proposed system and its control processes. In K.Spence (Ed.), The psychology of learning and motivation: Vol. 2. New York. Academic Press.

Azuma, R. (1993). Tracking Requirements for Augmentation Reality. July 1993, Vol. 36, No.7. Pp. 50-51.

Baecker, R., Small, I., & Mander R. (1991). Bringing Icons to Life. CHI '91 Conference Proceedings. Pp. 1-6.

Bailey, R.W. (1982). Human Performance Engineering: A Guide for System Designers. New Jersey: Prentice-Hall.

Bernstein, D.A.; Roy, E.J.; Srull, T.K. & Wickens, C.D. (1991). Psychology. (2nd Ed.) Houghton Mifflin Company, Boston.

Birren, F. (1978) Color and Human Response. Van Nostrand Reinhold Company.

Birren, F. (1992). Color Psychology and Color Theraphy. A Citadel Press Book.

Blattner, M.M., Sumikawa, D.A., & Greenberg, R.M. (1989). Earcons and icons: their structure and common design principles. Human-Computer Interaction, 4. Pp. 11-44.

Borgman, C.L. (1984). The user's mental model of an information retrieval system: effects on performance. Dissertation Abstracts International, 4A. Pp. 45.

Brazier, S. (1994). The Unseen Helping Hand, (Hewson, D.) The Sunday Times, Live '94 (18th September '94). Pp. 3.

Broadbent, D.E. (1958). Perception and Communication.

Brown, C. (1988). Human-Computer Interface Design Guidelines. Ablex.

BS1881:Part 204. (1988). Recommendations on the use of electromagnetic covermeters. British Standards Institute.

Burns, M.J.; Warren D.L.; & Rusidill, M. (1987). Formatting space-related displays to optimize expert and non-expert user performance. Proceedings of CHI'86 Conference on Human Factors in Computing Systems, Boston, Mass. New York: Association for Computing.

Byrne, M.D. (1993). Using Icons to Find Documents: Simplicity Is Critical, INTERCHI '93 Conference Proceedings. Pp. 446-453.

Byte Magazine (June 1994). Advertising Section. Hardware Showcase. Pp. 405.

Byte Magazine (Dec. 1995). Hidden Markov Models. Byte CD-ROM.

Byte Magazine (Feb. 1996). Alternative Input Spells Relief. News & Review. Pp. 28.

Byte Magazine (Feb 1996). Kantek Fingers a Better Mouse. What's New Hardware. Pp. 202.

Byte Magazine (July 1990). Reach Out and Touch Your Data. Pp. 283-290.

Byte Magazine (June 1994). 3-D Mouse. What's New International.

Byte Magazine (June 1995). Rewriting Handwriting Recognition.

Byte Magazine (Mar. 1996). I'll Talk to You Soon. Pp. 30.

Byte Magazine (May 1992). 3-D Displays. Byte CD-ROM.

Byte Magazine (Nov. 1992). Trackballs for Everyone. What's New

Byte Magazine (Oct. 1993). Pen Computing Catches On. State of the Art. Byte CD-ROM.

Byte Magazine (Oct. 1995). Help Gets Natural. News & Views. Pp. 30.

Byte Magazine (1991). Smart Use of Color in Displays. December Issue. Pp. 35-45.

Callan, J.R.; Curan, L.E.; & Lane, J.L. (1977). Visual Search Times for Navy Tactical Information Displays (Report ~ NPRDC-TR-77-32). San Diego, CA: Navy Personnel Research and Development Center. (NTIS No. A040543).

Card, S.K., English, W.K., & Burr, B.J. (1978). Evaluation of Mouse, Rate-Controlled Isometric Joystick, Step Keys, and Task Keys for Text Selection on a CRT. Ergonomics 21, 8. August Issue. Pp. 601-613.

Carino, N.J. (1993). Characterization of Electromagnetic Covermeters. Conference

Proceedings. Non-Destructive Testing in Civil Engineering. Vol.2. Pp. 753-765.

Carroll, J.M. & Mack, R.L. (1983). Actively learning to use a word processor. Cognitive aspects of skilled typewriting. W. Cooper (Ed.), New York: Springer-Verlag.

Carroll, J.M. & Mack, R.L. (1984). Learning to use a word processor: By doing, by thinking, and by knowing. In J.C. Thomas and M. Schneider (Eds.), Human factors in computers. Norwood: Ablex.

Carroll, J.M., Mack, R.L., & Kellogg, W.A. (1988). Interface Metaphors and User Interface Design. In M. Helander (Ed.), Handbook of Human-Computer Interaction. Elsevier Science Publisher B.V. (North-Holland). Pp. 67-81.

Carter, R.L. (1982). Visual search with color. Journal of Experimental Psychology: Human Perception and Performance, 8. Pp. 127-136.

CD-ROM Magazine (1995). Doom with Boom. Pp. 28-31.

CD-ROM Magazine (Feb. 1996). Forte VFX1. Pp. 90.

CD-ROM Magazine (Mar. 1996). World's first 3D PC VR Game. Pp. 16.

Champs, H. (1996). Choosing Colors: Not So Black and White. Web Developer. September/ October Issue. Pp. 40-41.

Christ, R.E. (1975). Review and Analysis of Color Coding Research for Visual Displays. Human Factors 17, No. 6. Pp.101-126.

Chua, J., Alldred, J., & Chamberlain, D. (1995). Determination of Reinforcing Bar Diameter and Cover by Analysing Traverse profiles from a Cover Meter. In Schickert, G., & Wiggenhauser, H. (Eds.), International Symposium Non-Destructive Testing in Civil Engineering. Vol. 1, Pp. 721-727.

Collie, A.A., Billengsley, J., & Luk, B.L. (1991). A Robot Climbing Vehicle and its Man-Machine Interface for use in the Nuclear Industry. 8th International Symposium on Automation and Robotics in Construction. Pp. 851-859.

Commission Internationale de l'Eclairage. (1978). Recommendations on Uniform Color Space, Color-differences equations, and Psychometric Color terms. Supplement No. 2 to CIE Publication No. 15.

Computer Buyer's Guide and Handbook, (1995). New Alternatives to Traditional Input. Vol. 8, Number 8. Pp. 54-67.

Cornsweet, T.N. (1970). Visual Perception. New York: Academic Press.

Cotton, B. & Oliver, R. (1995). The Cyberspace Lexicon.

Craik, K.J.W. (1943). The Nature of Explanation. Cambridge University Press.

Cringely, R.X. (1996). Accidental Empires. London: Penguin Books. Pp. 80-83.

Das Gupta, N.C. & Tam, C.T. (1983). Non-Destructive Technique for Simultaneous Detection of Size and Cover of Embedded Reinforcement. British Journal of NDT. Pg. 301-304.

de Souza, F. & Bevan, N. (1990). The Use of Guidelines in Menu Interface Evaluation and its

Integration in a UIMS. In Diapers, D.; Gilmore, D.; Cockton, G.; & Shackel, B. (Eds.). Human-Computer Interaction - Interact'90. North-Holland. Pp. 435-440.

Deichsel & Krell (1987). Bestimmung der Betondeckung der Bewehrung am Bauwerk. Beton 37.

Dodson, D.W. & Shields, N.L., Jr. (1978). Development of User Guidelines for ECAS Display Design (Vol. 1) (Report No. NASA-CR-150877). Huntsville, AL: Essex Corp.

Douglas, S. & Moran, T. (1983). Learning text-editing semantics by analogy. Proceedings of CHI'83 Conference on Human Factors in Computer Systems, Boston, Massachusetts. New York: ACM. Pp 207-211.

Durret, H.J. (1987). Color and the Computer. Academic Press, Inc.

Ebbinghaus, H. (1885). Memory: A Contribution to Experimental Psychology. In H.A. Roger & C.E. Bussenius, Trans., 1913. N.Y. Columbia University Press.

Elliott, M.F. (1993). Iconic reference: evolving perspectives and an organizing framework, 33. Pp. 705-728.

Ellis, J.G., & Dewar, R.E. (1979). Rapid Comprehension of Verbal and Symbolic Traffic Sign Messages. Human Factors, 21. Pp.161-168.

English, W.K., Engelbart, D.C. & Berman, M.L. (1967). Display Selection Techniques for Text Manipulation. IEEE Transactions on Human Factors in Electronics, HFE-8, 1, March Issue. Pp. 5-15.

Eysenck, H.J. (1941). A Critical and Experimental Study of Colour Preferences, American Journal of Psychology, July Issue.

Facaoaru, I. (1969). Non-destructive testing of concrete in Romania. I.C.E. Symposium on Non-Destructive Testing of Concrete and Timber, London, June 11-12.

Fink, B., Hiller, M., Krölls, H., & Schweikart, S. (1996). Concepts of an Avanced Cartesian Control System for a Redundant Twin Boom Drill Rig. In M.K. Maeda (Ed.), The 13th International Symposium on Automation and Robotics in Construction. Pp. 103-111.

Folley, J.D., Wallace, V.L., & Chan, P. (1984). The Human Factors of Computer Graphics Interaction Techniques. IEEE Computer Graphics and Applications 4, 11. Pp. 13-48.

G. Davenport (1993). Voice Assist User's Guide. Creative Technology Ltd.

H.

Gaines, B.R. (1984). From Ergonomics to the Fifth Generation: 30 Years of Human-Computer Interaction Studies. In B. Shackel (Ed.), Human-Computer Interaction - INTERACT'84. Elsevier Science Publishers B.V. (North-Holland). Pp. 3-7.

Galitz, W.O. (1993). User-Interface Design, Workstations, P.C.'s and Mainframes. QED Publishing Group. Pp. 394.

Galitz, W.O. (1993). User Interface Screen Design, 2nd Ed., QED Pulishing Group, Wellesley, MA. Pp.425-451.

Gaver, W.W. (1986). Auditory icons: using sound in computer interfaces. Human-Computer Interaction, 2. Pp. 167-177.

Gaver, W.W. (1989). The SonicFinder: An Interface That Uses Auditory Icons. Human-Computer Interaction. 4. Pp. 67-94.

Gaydecki, P., Glossop, K. & Burdekin, F. (1995). A prototype inductive scanning system for two-dimensional imaging of metal reinforcing components in concrete: system design and data visualization. In Schickert, G., & Wiggenhauser, H. (Eds.), International Symposium Ono-Destructive Testing in Civil Engineering. Pp. 745-752.

Gentner, D. (1983). Structure mapping: A theoretical framework for analogy. Cognitive Science, 7. Pp. 155-170.

Gick, M.L. & Holyoak, K.J. (1983). Analogical problem solving. Cognitive Psychology, Vol. 12. Pp. 578-579.

Green, A.J.K. & Barnard, P.J. (1990). Iconic Interfacing: The Role of Icon Distinctiveness and Fixed or Variable Screen Locations. Human-Computer Interaction. Pp. 457-462.

Gregory, R. L. (1968). Visual illusions. Scientific American, Vol. 219. Pp. 66-67.

Gregory, R. L. (1973). The Eye and Brain (2nd Ed.). New York: McGraw Hill.

Haber, R. N. (1970). How We Remember What We See, Scientific American, May Issue. Pp. 104-112.

Halasz, F.G. (1984). Mental models and problem solving in using a calculator. Doctoral dissertation, Stanford University, CA, USA. Dissertations Abstracts International, Vol 45. Pp. 1046B-1047B.

Haller, R., Mutschler, H. & Voss, M. (1984). Comparison of Input Devices for Correction of Typing Errors in Office Systems. INTERACT 84. Pp. 218-223.

Hemenway, K. (1982). Psychological Issues in the Use of Icons in Command Menus. Proceedings of Human Factors Society 26th Annual Meeting, Seattle, WA., October Issue.

Hockey, R. (1986). Varieties of attentional state: The effects of environments. In R. Paraduraman & R. Davies (Ed.), Varieties of attention. New York: Academic Press.

Horton, W. K. (1994). The Icon Book. Visual Symbols for Computer Systems and Documentation. John Wiley & Sons, Inc. Publication.

Human Factors Society, (1988). American national standard for human factors engineering of visual display terminal workstations. Santa Monica, CA: Author.

Hutchins, E.L., Hollan, J.D., & Norman, D.A. (1986). Direct Manipulation Interfaces. User centered user system design: New perspectives on human-computer interaction. Pp. 87-124, 1986.

IBM Corporation. (1992). Object-Oriented Interface Design: IBM CUA Guidelines. New York: QUE.

International Business Machines (1987). IBM's System Application Architecture: Common User Access, Panel Design and User Interaction. SC26-4351-0, IBM, Boca Raton, FL.

Jacob, R.J.K. (1993). Eye-Gaze Computer Interfaces. Computer IEEE, July 1993. Pp. 65-67.

Jacobson, L. (1993). Welcome to the Virtual World. On the Cutting Edge of Technology. Pp. 70-80.

Johnson, J. (1987). How faithfully should the electronic office simulate the real one. SIGCHI Bulletin, 19. Pp. 21-24.

Kaneko, S., Ikemoto, H., & Kusui, Y. (1991), Approach to Designing Easy-to Understand Icons. IEEE. Pp. 246-253.

Karrat, J., McDonald, J. & Anderson, M. (1984). A Comparison of Selection Techniques: Touch Panel, Mouse and Keyboard. INTERACT 84. Pp. 149-153.

Keates, J.S. (1962). "The Perception of Colour in Cartography." Proceedings of the Cartographic Symposium, University of Glasgow. Pp. 19-28.

Keister, R.S. & Gallaway, G.R. (1983). Making Software User Friendly: An Assessment on Data Entry Performance. Proceedings of Human Factors Society 27th Annual Meeting. Pp. 1031-1034. Santa Monica, CA: Human Factors Society.

Kolers, P. (1969). Some Formal Characteristics of Pictograms. American Scientist, 57, 3. Pp. 348-363.

Kopala, C.J. (1981). The Use of Color Coded Symbols in a Highly Dense Situation Display. Proceedings of the Human Factors Society-23rd Annual Meeting, Santa Monica, CA. Pp. 736-740.

Kreb, M. & Wolf, J. (1979). Design principles for the use of color displays. Proceedings of the society for Information Display, 20. Pp. 10-15.

Kreb, M.J., Wolf, J.D. & Sandvig, J.H. (1978). Color Display Design Guide. Office of Naval Research Report, ONR-CR213-136-2F.

Krueger, M. (1983). Artificial Reality. Reading, MA: Addison-Wesley Publishing Company.

L"wgren, J. & Nordqvist, T. (1992). Knowledge-based Evaluation as Design Support for Graphical User Interfaces. Human Factors In Computing Systems. Proceedings CHI'92. ACM Press. Pp. 181-188.

Lakoff. G & Johnson, M. (1980). Metaphors We Live By. The University of Chicago Press, Chicago, 1980.

Laptop Buyer's Guide (1996). Look Ma, No Hands!, Bulletin Board. Vol. 14. Number 1. Pp. 10.

Larkin, J.H. (1983). The role of problem representation in physics. In D. Gentner & A.L. Stevens (Eds.), Mental Models. Hillsdale, NJ: Lawrence Erlbaum Associates. Pp. 75-98.

Laurel, B. (1990). Interface Agents: Metaphors with Character. In B. Laurel (Ed.), The Art of Human Computer Interface Design. Pp. 355-365.

Leibowitz, H.W., Brislin, R., Perlmutter,L., & Hennessy, R. (1969). Ponzo perspective illusion as a manifestation of space perception. Science, Vol. 166. Pp. 1174-1176.

Lindsay, P.H., & Norman, D.A. (1977). Human information processing. (2nd Ed.). New York: Academic Press.

Lodding, K. (1983). Iconic Interfacing. IEEE Computer Graphics and Applications, 3(2), March/ April Issue, pp. 11-20.

Lyold, C. (1994). Are You Ready For The Future, The Sunday Times, (20th November '94): pp. 16-17.

Mack, R.L., Lewis C. & Carroll, J.M. (1983). Learning to use office systems: Problems and prospects. ACM Transactions on Office Information Systems, Vol.1. Pp. 254-271.

Mack, R.L., Lewis, C. & Carroll, J.M., (1983). Learning to use office systems: Observations on requirements, usage, and interfaces. Research Report RC 12677, IBM Thomas J, Watson Research Center, Yorktown Heights, N.Y. 10598.

MacUser (1996). Windows OS enters age of Internet integration. July, 1996 Issue. Pp. 44.

MacUser (1996). The State of 8. August, 1996 Issue. Pp. 69-75.

Mansur, D.L., Blattner, M.M., & Joy, K.I. (1985). Sound-graphs: A numerical data analysis method for the blind. Proceedings of the 18th Hawaii International Conference on System Sciences, 18, January Issue.Pp. 63-174.

Marcus, A. (1984). Corporate identity for iconic interface design: the graphic design perspective. IEEE Computer Graphics & Applications, 4. Pp. 24-32.

Martin, J. (1973). Design of Man-Computer Dialogues. Anglewood Cliffs NJ, Prentice-Hall.

Mayer, R.E. (1981). The psychology of how novices learn computer programming. Association for Computing Machinery Computing Surveys, Vol. 13. Pp. 121-141.

Mayhew, D. (1992). Principles and Guidelines in Software User Interface Design. New Jersey: Prentice-Hall.

Microsoft Corporation. (1992). The Windows Interface: An Application Design Guide. Microsoft Press. Redmond, Washington.

Miller, G.A. (1956). The magical number seven, plus or minus two. Some limits on our capacity to process information. Psychological Review, Vol. 63. Pp. 81-97.

Moran, T.P. (1981). The command language grammar: a representation for the user of interactive systems. International Journal of Man-Machine Studies, Vol. 15. Pp. 3-50.

Mountford, S.J. (1990). Tools and Techniques for Creative Design. In B. Laurel (Ed.), The Art of Human Computer Interface Design. Pp. 17-30.

Murata, A. (1991). An Experimental Evaluation of Mouse, Joystick, Joycard, Lightpen, Trackball and Touchscreen for Pointing. Basic Study on Human Interface Design. In H.J. Bullinger (Ed.), Human Aspects in Computing: Design & Use of Interactive Systems & Work with Terminals. Elsevier Science Publishers B.V. Pp. 123-127.

Murch, G. (1983). The Effective Use of Color: Physiological Principles. Tektronix, Inc. 4p.

Murch, G. (1984A). The Effective Use of Color: Perceptual Principles. Tektronix, Inc. 6p.

Murch, G. (1984B). The Effective Use of Color: Cognitive Principles. Tektronix, Inc. 7p.

Nelson, R.P. (1981). The Design of Advertising, Wm. Brown Co., Dubuque, Iowa.

Norman, D.A. (1983). Some observations on mental models. In D. Gentner and A.L. Stevens (Eds.), Mental Models. Hillsdale, N.J., Erlbaum. Pp. 7-14.

Norman, D.A. (1986). Cognitive Engineering. In D.A. Norman & S.W. Draper (Eds.), User-centered system design. Hillsdale, NJ, Erlbaum. Pp. 67-85.

Norman, K.C. (1991). The Psychology of Menu Selection. Pp. 189-213.

Olson, J.M. (1987). Color and the Computer in Cartography. In Color and the Computer. Durret, H.J. (Ed) Orlando, FL: Academic Press. Pp. 205-220.

Ostberg, W.C. & Boyle, J.M. (1982). Evaluating Human-Computer Dialogue Styles: Command vs. Form/Fill-in for Report Modification. In Proceedings of the Human Factors Society-26th Annual Meeting, Santa Monica, CA. Pp. 542-545.

Pastoor, S. (1990). Legibility and Subjective preference for Color Combinations in Text. Human Factors, 32. Pp. 157-171.

PC Magazine (Jan. 1994). Get to Grips with the Latest Joysticks. After Hour. Pp. 354.

PC Magazine (Mar. 1995). Compaq Enters the Kids' Market with Fisher-Price. Trends Section. Pp. 31.

PC Magazine (Oct. 1994). Key Health Issues: Economics Over Ergonomics. Trends Section. Pp. 33.

PC Pro Magazine (Oct. 1996). Taking Talking Lessons. Pp. 46.

PC Pro Magazine (Sept. 1996). Notebooks A Go-Go. Pp. 207-212.

Pearson, G. & Weiser, M. (1986). Of Moles and Men: The Design of Foot Controls for Workstations. Proceedings ACM CHI'86: Human Factors in Computing Systems, ACM, N.Y. Pp. 333-339.

Pen Computing Magazine (June 1995). News, Rumors, and Gossip in the World of Pens.

Personal Computer World (Feb. 1996). Gyrations GyraPoint Desk. Gadgets. Pp. 57.

Personal Computer World (Feb. 1996). Wacom UltraPad A5 Graphics Tablet. Pp. 74.

Personal Computer World (Mar. 1996). Chance Your Arm on BT's Portable Office. Pp. 26.

Peterson, L.R., & Peterson, M.J. (1959). Short-term retention of individual verbal items. Journal of Experimental Psychology, Vol. 58. Pp. 193-198.

Pierce, C.S. (1955). Logic as semiotic: the theory of signs. In J. Buchler, Ed. Philosophical Writings of Pierce. New York: Dover Publications. Pp. 98-128.

Pomerantz, J.R. 1983). Global and local precedence: selective attention in form and motion perception, Journal of Experimental Psychology: General 112. Pp. 516-540.

Pöpel, M., & Flohrer, C. (1995). Combination of a Covermeter with a Radar System - an Improvement of Radar Application in Civil Engineering. In Schickert, G., & Wiggenhauser, H. (Eds.), International Symposium Non-Destructive Testing in Civil Engineering. Pp. 737-743.

Ramachandran, V.S. (August, 1988). Perceiving shape from shading. Scientific American. Pp. 76-83.

Ricken, W., Mehlhorn, G., & Becker, W. (1995). Determining of the concrete cover thickness and bar diameter in reinforced concrete with a method of eddy current testing. In Schickert, G., & Wiggenhauser, H. (Eds.), International Symposium Non-Destructive Testing in Civil Engineering. Pp. 197-204.

Roger, Y. (1989). Icons at the interface: their usefulness. Interacting with Computers, 1. Pp. 105-117.

Rogers, Y. (1986). Evaluating the meaningfulness of icon sets to represent command operations. Proceedings of HCI'86 Conference on People and Computers: Designing for Usability. North Holland: Elsevier Science Publishers. Pp. 586-603.

Rösch, A., & Schaab, A. (1995). An in-situ NDT-method to detect incorrectly positioned dowel bars in carriageway slabs of concrete highway. In Schickert, G., & Wiggenhauser, H. (Eds.), International Symposium Non-Destructive Testing in Civil Engineering. Pp. 269-276.

Sackman, H. (1970). Man-Computer Problem Solving. Princeton. Auerbach.

Saloman, G & Chen J. (1989). "Using Neural Nets to Aid Color Selection." Society for Information Display International Symposium Digest of Technical Papers. Vol. 20, May Issue.Pp. 326-329.

Salomon, G. (1990) New Uses for Color. In B. Laurel (Ed.), The Art of Human Computer Interface Design. Pp. 269-278.

Seymore, Jim. (1992b). Opinion: A High 'UQ' Is What Spells Business Success. PC Week (October 5). Pp. 63.

Seymour, Jim. (1992a). The Corporate Manager: No Doubt About It, 1992 Was the Year of Usability. PC Week (December 21). Pp. 65.

Shackel, B. (1984). The Concept of Usability. The Visual Display Terminal: Usability Issues and Health Concerns, J. Bennet, D. Case, J. Sandelin, and M.Smith (eds.) New York: Prentice-Hall. Elsevier Science Publishers B.V. (North-Holland). Pp. 45-88.

Shackel, B. (1991). Whence And Where - A Short History of Human-Computer Interaction. In H.J. Bullinger (Ed.), Human Aspects in Computing: Design and Use of Interactive Systems and Work with Terminals. Pp. 4- 8.

Shepard, R. (1967). Recognition memory for words, sentences and pictures. Journal of Verbal Learning and Verbal Behavior, 6. Pp. 156-163.

Shirley, D.E. (1971). Electromagnetic Covermeters. British Journal of Non-Destructive Testing. Pp 179-180.

Shneiderman, B. (1992). Designing the User Interface, Strategies for Effective Human-Computer Interaction, 2nd Ed., Addison-Wesley Publishing Company, Inc. Pp. 325-330.

Shneiderman, B., and Margono. (1987). S., A study of File Manipulation by Novices Using Comands vs. Direct Manipulation. Proceedings of 26th Annual Technical Symposium of the Washington, DC. Chapter of the ACM. Gaithersburg, MD: National Bureau of Standards.

Sidorsky, R.C. (1982). Color Coding in Tactical Displays: Help or Hindrance. Army Research Institute Research Report.

Sivak, J.G. & Woo, G.C. (1983). Color of visual display terminals and the eye: Green VDT's provoke the optimal stimulus to accommodation. American Journal of Optometry and Physiological Optics, 60. Pp. 640-642.

Smith, D.C. (1982). Designing the Star User Interface. Byte Publications Inc., April Issue. Pp. 242-282.

Smith, S.L. & Mosier, J.N. (1986). Guidelines for Designing User Interface Software. Prepared for Deputy Commander for Development Plans and Support Systems, Electronic Systems Division, AFSC, USAF, Hanscom AFB, MA. Mitre ESD-TR-86-278 MTR 10090.

Sperling, G. (1960). The information available in brief information presentations. Psychological

Monographs, Vol. 74. Pp1-29.

Staggers, N. & Norcio, A.F. (1993). Mental models: concepts for human-computer interaction research. International Journal of Man-Machine-Systems. Vol. 38. Pp. 587-606.

Stammers, R.B., & Bird, J.M. (1980). Controller Evaluation of a Touch Input Air Traffic Data System: An Indelicate Experiment. Human Factors 22, 5. Pp. 581-589.

Standing, L. (1973). "Learing 10,000 Pictures," Quarterly Experimental Psychology, Vol. 25, No. 2. Pp.207-222.

Standing, L., Cornezio, J. and Haber, R.N. (1970). "Perception and Memory for Pictures: Single-Trial Learning of 2500 Visual Stimuli," Psychonomic Sci., Vol 19. Pp.73-74.

Sun Microsystems, Inc. (1990). OPEN LOOK: Graphical User Interface Application Style Guidelines, Addison-Wesley, Reading, MA.

Tam, C.T.; Lai, L.N. & Lam P.W. (1977). Orthogonal Detection Technique for Determination of Size and Cover of Embedded Reinforcement. Journal of the Institute of Engineers of Malaysia. Vol. 22. Pp. 6-16.

Thacker, P. (1987). Tabular Displays: A Human Factors Study. CSTG Bulletin, 14, (1) Human Factors Society. Pp. 13.

The Sunday Times (16 Apr. 1995). The Internet? It's all in the mind. News Section. Pp. 15.

The Sunday Times (21 Apr. 1994). Electronic 'muscles' for Disabled. Innovation Section. Pp. 11.

The Sunday Times (Sept. 1994). Getting to know you - and all about you. Business Technology Section. Pp. 7.

Thompson, P. (1984). Fundamentals of Human-Computer Interaction. London. Academic Press. Pp. 5-33.

Thorndike, E.L. (1898). Animal Intelligence: An experimental study of the associative processes in animals. Psychological Monographs, 2.

Thovtrup, H. & Nielson, J. (1991). Assessing the Usability of a User Interface Standard. Human Factors in Computing Systems, Proceedings CHI'91. Pp. 335-342.

Tollet, P. (1994). The Unseen Helping Hand, (Hewson, D.) The Sunday Times, Live '94 (18th September '94). Pp. 3.

Tomkins, S. (1996). HILITES database on CD-ROM. HUSAT Research Institute.

Tourangaeu, R. & Sternberg, R. (1882). Understanding and appreciating metaphors. Cognition. 11. Pp. 203-244.

Travis, D. (1991). Effective Colour Displays, Theory and Practice, Academic Press.

Treisman, A. (1982). Perceptual Grouping and Attention in Visual Search for Features and Objects. Journal of Experimental Psychology: Human Perception and Performance, 8. Pp. 194-214.

Tullis, T.S. (1981). An Evaluation of Alphanumeric, Graphic and Color Information Displays. Human Factors, 23. Pp. 541-550.

Tullis, T.S. (1983). The Formatting of Alphanumeric Displays: A Review and Analysis. Human Factors, 25. Pp. 657-682.

Tullis, T.S. (1984). Predicting the Usability of Alphanumeric Displays. Ph.D. Dissertation, Rice University. Lawrence, Kansas: The Report Store.

Tulving, E. (1985). How many memory systems are there? American Psychologist, Vol. 40. Pp. 385-398.

Vanderveer, N.J. (1979). Ecological acoustics: Human perception of environmental sounds. Dissertation Abstracts International, 40/09B, 4543. (University Microfilms No. 8004002).

Verity, E. (1980). Color Observed. New York: Van Nostrand Reinhold.

Walls, G.L. (1942). The Vertebrate Eye, Cranbrook Press.

Walls, G.L. (1944). The Basis of Night Vision, Illuminating Engineering.

Walraven, J. (984). Perception Artifacts that may Interfere with the Color Coding in Visual Displays. Proceedings of NATO Workshop: Color Coded vs. Monochrome Electronic Displays, C.P. Gibson (Ed.) Fanborough, England: Royal Aircraft Establishment. Pp. 13.

Waterworth, J.A., Chignell, M H. & Zhai, S.M. (1993). From icons to interface models: designing hypermedia from the bottom up. International Journal of Man-Machine Systems. 33. Pp. 453-472.

Webb, J. M., Sorenson, P. F., & Lyons, N.P. (1989). An empirical approach to the evaluation of icons. SIGCHI Bulletin, 21. Pp. 87-90.

Weinberg, G.M. (1971). The Psychology of Computer Programming. New York, Van Nostrand Reinhold.

Wheen, R.J. (1974). Non-Destructive Testing of Concrete. Building Science, Vol. 9. Pp 157-166.

Whittaker, W.L. (1987). Cognitive Robots for Construction. Construction Robotics Laboratory, USA. Pp. 7-16.

Wickens, C.D. (1989). Attention. In D. Holding (Ed.), Human skills. New York: Wiley.

Wickens, D.D. (1972). Characteristics of word encoding. In A.W. Melton & E. martin (Eds.), Coding processes in human memory. Washinton DC: Winston.

Windows Magazine (Jan. 1996). How to buy a pointing device. Pp. 241.

Winograd, T. (1972). Understanding Natural Language. Edinburgh, The University Press.