The Application of Data Fusion to Reinforced Concrete NDT

[Experimental Data in Separate Volume]

By

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Abstract

Research into different approaches to concrete non-destructive testing is presented. However, the main consideration is how data fusion methods can add value to the interpretation of the data gathered from different sensor sources. Mathematical models for data fusion and simultaneous adjustment of inhomogeneous data are used, which increase the accuracy and reliability of the subsequent surface repair decision.

The aim of the approach is to adjust any kind of data in a combined way by giving adequate weights to each measurement. An assessment of the quality of different sensor data is part of this. A comparison of different sensors is given.

A Graphical User Interface, developed in the research, gives surface representations of the spatial data. This allows the differences between surface reconstruction results to be examined.

The validation of the approach for multi sensor fusion for the reconstruction of surfaces is described and demonstrated by using data from areas of concrete that have been surveyed and subsequently repaired.

The results of the numerical experiments are interpreted and conclusions for the processing chain of the approach drawn. With further development the experimental software could be useful for industrial applications.

Table of Contents

Chapter 1

INTRODUCTION

1 INTRODUCTION

1.1 Introduction

Non-destructive tests are powerful and economic tools that can be used to investigate structures. These tests will be referred to as NDT, as it is commonly called. It gained this from the way these tests are carried out. For a number of years civil engineers has been involved in finding the most efficient way to investigate structures and determine their condition. NDT has attracted much attention and has been improved in terms of results and feedback throughout the past years, and many papers have been published. There is no denying that the data fusion concept is relatively simple but its implementation remains challenging. In this context, the term 'multi-sensor fusion' refers to the acquisition, processing and synergistic combination of information gathered by various knowledge sensor, to provide a better understanding of the phenomenon under consideration. [E. Gros, 2001]

The use of multiple sensors for NDT and the integration of information from these sensors have been applied as early as 1989. Computer tomography, eddy current and ultrasonic data were interpolated synergistically to a common pixel raster format for comparison, but no data fusion operation was performed, for example. Since then, new advances in the field of NDT signal processing and NDT data fusion have been accomplished. [J. Nelson, 1989]

1.2 Aim

The aim of the research is to investigate whether or not data fusion methods can be usefully applied to the interpretation of data from a number of different NDT devices used in concrete inspection. This will be evaluated by comparing prediction outcomes with the material findings for an actual bridge repair project, since different locations were tested using NDT equipments on the bridge. The main prediction is the decision whether or not the concrete is sufficiently deteriorated to demand repair and improvement. The researcher had no prior knowledge of the findings during preparation and execution of the repair work. Data gathered from a laboratory investigation on a small slab will be used in an early stage of the study.

1.3 Background

1.3.1 Inspection & Repair Demand

Reinforced concrete deterioration is a large and growing problem. A significant reason for its decay is acid rain, which is reducing the alkalinity of the near to surface concrete region. This is unfortunate because is it also the region in which the first layer of reinforcing steel is located. With loss of alkalinity, the steel reinforcement, upon which the durability and strength of the structure depends, is vulnerable to corrosion.

To get some impression of the scale of the potential problem, table (1.1) gives the approximate surface area of concrete roads in the European Community.

CLASS	LENGTH (km)	AVE. WIDTH (m)	SURFACE AREA (109m2)	EXPOSED CONCRETE PORTION (x109m2)
Motorways	51,004	30	1.53	0.459
Major Roads	224,175	12	2.69	0.807
Other Paved Roads	3,196,927	6	18.18	3.836
			TOTAL =	5.102 x 109m2

Table (1.1) Total Highway Pavement in the Table (1.1) European Community at 1997 [Based on data from British Road Federation, London, UK]

Further to this, regarding road and rail bridges, there are estimated to be currently 150,000 in the UK alone and a total of 900,000 in the EC, [Based on data from British Concrete Association, Berkshire, UK]. The average area of decking is taken as 150 m^2 per bridge and otherwise exposed concrete at 200 m2/bridge, giving EC totals of 0.13 x 109m2 over coated decking and 0.18 x 109m2 exposed concrete. Although bridge decks are coated, they commonly exhibit the same problems as the exposed areas. These areas are thus combined as (0.31 x 109) m2. The replacement value of these bridges would be in excess of 900 BEuro's, the majority of which are more than 30 years old.

Table (1.2) refers to public sector housing, which are so called tower blocks/flats built mainly in the mid 1960's to late 1970's. The statistics are

CLASS	DWELLINGS	AVE. SURFACE AREA/DWELLING (m2)	EXPOSED CONCRETE (x 109m2)
6-11 Storeys	1,952,000	10m2 (20% of 50)	0.195
12 + Storeys	1,360,000	35 m2 (70% of 50)	0.057
		TOTAL =	0.252 109m2

Table (1.2) Exposed Concrete Surface for 6+ Storey Buildings in the European Community [Based on Government Housing Stock Statistics Published in the European Community]

estimates for reinforced concrete system build structures, having a replacement cost in excess of 100 BEuro's.

1.3.2 Improving Inspection

From the above it can be seen that concrete deterioration has potentially an extremely high monetary consequence. For this reason, respecting that the available funds will inevitably be limited, it is most important that priorities can be reliably set in the repair work. Reliable non-destructive testing can give a sure basis for this. However, detailed surveys are frequently costly and thus unattractive to the client. For this reason it is important that survey work is an optimised activity, giving the best information for the limited resource. This is where data fusion methods offer help, in that it gives the way to adding significant value to test data.

Data fusion methodology is able to take into account the individual accuracies of the different methods and feed this into a system that gives a combined outcome that has itself a known degree of certainty. However, whilst humans operate natural data fusion systems in apparently mundane activity, walking for example, it is not easy to represent human intelligence in a computer based data fusion system. It is thus the aim of this research to make a contribution in this area, by researching, developing and testing data fusion models for NET data. Hopefully, in the future, there will exist dependable, real-time data fusion systems that are of great benefit in condition assessment and repair priority setting of reinforced concrete structures.

1.4 Objectives of the Research:

The objectives of this research are as follows:

- To review the nature of the deterioration of reinforced concrete structures
- To review Non-Destructive Testing (NDT) methods and select a reduced set of methods for the purposes of a data fusion study
- To review and investigate data fusion methods that are suitable for the NDT data
- To build and test a data fusion model for combining the NDT data
- To investigate, incorporate and test the use of artificial intelligence in a data fusion model, including the use of a real case study.

1.5 Scope of Work

There is an accumulation of NDT techniques and systems for testing reinforced concrete. Further to this, there are in most cases rival systems of the same type. Complete coverage of all NDT systems is outside the scope of this research. For this reason, only a reduced set of methods has been adopted. In spite of this, it is important to note that they rely on distinctly different physical phenomena and produce different output types. The combined use of them is also not a simple matter of averaging or other techniques, which could result in meaningless numbers. Knowledge of the significance of the individual readings and that of co-occurrence data sets needs to be applied. For this reason, the inclusion of artificial intelligence has been researched. Whilst the research would appear to lack generality, it is observed that the ideas could be re-examined for other combinations of NDT methods.

1.6 Research Methodology

In sequence, the approach to the research has been to (i) undertake reviews in order to understand the nature of concrete deterioration, non-destructive testing techniques and the state of the art in data fusion methods, (ii) develop and test a first stage experimental computer programme for data fusion, applying a weighting method, (iii) extend the Stage 1 experimental software by incorporating certainty and other statistical processes together with a new graphical interface and (iv) test and conclude on the data fusion approach to NDT interpretation using real case study data.

1.6.1 Review of concrete deterioration

A review of the nature of reinforced concrete deterioration has been completed to understand this at a practical level. The principal causes are bad design and detailing, poor workmanship at the construction phase and the generally aggressive environment this effect has only been acknowledged in the past 15-20 years. This material is well covered in published literature and the author includes only a summary in this thesis.

1.6.2 Review of non-destructive testing

A review of Non-Destructive Testing methods has been completed. However, for the purposes of the research, it is necessary to limit the number of methods for the data fusion study. A significant influence in the choice of NDT methods for this is their immediate availability to the author. The instrumentation readily available includes:

- Visual survey for gross physical defects and indicative manifestations such as surface oxide staining.
- Rebar detection.
- Rebound hammer for indirect strength estimation.
- Half-cell potential for detection of corrosion activity.

These are considered to be a useful set because they are different types of data on different aspects of the deterioration problem. Their data cannot simply be averaged, for example. As with material under Objective 1, NDT methods are explained widely in the literature, thus this thesis only includes a summary of the more relevant NDT methods.

1.6.3 Review of data fusion techniques

A review of the many approaches to data fusion has been undertaken. In this research, it is clear that most methods are more suitable for combining identical data forms, for example for a bank of identical sensors, then dealing with multiple sensors of different types with different data and interpretation. This point brings out the main significance of this research in that NDT data fusion is less straightforward than conventional data fusion applications. An example of the later is found in aircraft safety system where simple voting methods are effectively applied to a bank of identical redundant sensors all measuring the same critical quality.

1.6.4 Development and testing of Stage 1 programme

A Stage 1 data fusion computer programme has been encoded and evaluated. This combines data for Concrete Cover (rebar detector), Insitu Strength (rebound hammer) and Corrosion Activity (half cell potential). A combination of statistical processing of the raw data and weighted averaging has been employed. The accepted interpretation of each sensor's critical output values, half-cell value for no-corrosion activity, for example, is built into the programme. A demonstration run of this programme, using dummy data, is presented. This is effective, but relies on considerable user expertise in applying weightings and evaluating the significance of the data combinations. A combination of Visual

Basic and an Excel Spread Sheet has been used to develop this Stage 1 computer program. A simple 200mm * 400mm slab is used in laboratory for NDT data gathering

1.6.5 Refinement of Stage 1 programme and experiments (Stage 2)

Work under this objective represents the bulk of the work in the research. The Stage 1 program is effective but only when used by someone with experience in NDT survey and an understanding of the combined decay indicators, obvious voltaic activity combined with low rebar cover, for example. For such computer tools to be of benefit, useful human intelligence needs to be captured and encoded. A rule based, expert system is investigated to cover this. To allow reliability of outcomes to be represented, however, Bayesian certainty is used in the model. Thus, the objects of the rules, the sensor values, have certainties and these are combined through rule sets to give a corresponding certainty in the outcome. A complication is the spatial relationship between data, which is not unlike that found with image processing. Experiments run with this tool are derived for actual inspection and repair projects on a bridge structure. Six different locations on the bridge were used for data collection and condition testing.

1.7 Structure of the thesis

Firstly, in chapter 2, a summary review is presented of defects that commonly occur in reinforced concrete structures. Reflecting the sequence of the work undertaken, this is followed by a review in chapter 3 of NDT methods. A review of data fusion methods is then presented in chapter 4, followed by an account of a data fusion model devised for testing initial ideas in chapter 5. Following observations on this, an account is given in chapter 6 of the artificial intelligence that is applied to improve the data fusion process. Rule based logic is applied in this. Conclusions drawn from the numerical experiments in data fusion are given in chapter 7. The consolidated conclusions of the research are given in chapter 8. Experimental data, including that used in the case study in contained in a separate volume.

CHAPTER 2

Characteristics of concrete deterioration

2 CHARACTERISTICS OF CONCRETE DETERIORATION

2.1 Introduction

The purpose of this chapter is to review the physical characteristics of concrete deterioration. As appropriate, these are related to the quantities that NDT methods address, for example, measurable electrical resistance.

This chapter aims to give a general background to the deterioration of concrete. Many of the issues concerning the deterioration of concrete will be discussed in this chapter. Broadly speaking, problems with concrete can be classified into four sections:

- Initial design errors: either structural or in the assessment of environmental exposure.
- Built-in problems: the concrete itself can have built-in problem. A good example of this alkali silica reaction, where the alkalinity in the concrete paste reacts with the aggregate; this reaction producing an expansive gel that can cause extensive cracking.
- Construction defects: poor workmanship and site practice can create points of weakness in concrete that may accelerate the long-term deterioration of the structure. A common defect of this type is poor curing of the concrete. This result in a permeable concrete, which can lead to the accelerated deterioration of a structure faced with an aggressive environment.
- Environmental deterioration: a structure has to satisfy the requirement of resistance against the external environment. Problems may occur in the form of physical agents such as abrasion, and biological or chemical attack such as sulphate attack from ground water. The key issue here is; what is the mechanism of attack and how severe is it? [F. Rendell, 2002]

2.2 Problems with concrete

Details of these main problems are given in the following sections.

2.2.1 Built-in problems in concrete

In its simplest form, the principal components of concrete are cement, sand, aggregate, and water. The chemical reaction between cement and water produce a stone-like material, not dissimilar to limestone conglomerate. Steel reinforcement is cast into concrete to augment the shear and tensile properties of the material. This steel is generally in a passive condition, i.e. it will not rust. [F. Rendell 2002]

2.2.2 Construction defects

Poor site practice during the fabrication of concrete work may lead to problems that surface years after the structure is put into service.

2.2.2.1 Poor compaction

Often resulting from operatives increasing the workability by adding water to the mix before placing, resulting in low strength and highly porosity.

2.2.2.2 Poor curing

This is one of the most common causes of reduced material durability. The curing of concrete is intrinsically linked to the hydration of the cement and therefore the strength gain and porosity.

2.2.2.3 Thermal cracking

Typically, concrete can gain in temperature about 14°C per 100 kg of cement in a cubic meter of concrete. In large pours this sets up a thermal gradient, with the outer part of the concrete cooling more rapidly than the core, putting the outer skin in tension with small cracks forming.

2.2.2.4 Plastic settlement cracks

Plastic settlement cracks are typically found in columns, deep beams or walls. The problem tends to occur in concretes with a high water/cement (W/C) ratio which have suffered from bleeding.

2.2.2.5 Plastic shrinkage

This type of shrinkage can occur when the rate of water loss from evaporation exceeds the rate at which bleeding (movement of water to the surface) can occur. This leads to a surface network of cracks as one would see in clay that has dried in the sun.

2.2.2.6 Low cover

This is a common site defect with is, the result of either poor concrete design detailing or poor site control. [F. Rendell, 2002]

2.2.3 Environmental deterioration

Any rationalisation of the deterioration process is intrinsically flawed because of the complexity of the material and the exposure environment. In many cases a concrete will suffer from several concomitant vectors of attack. Any mechanism of attack that weakens the materials will generally open the way for other mechanisms that weaken the material further.

2.2.4 Corrosion Risk

The corrosion that can occur in reinforcing steel is usually a result of a electrochemical reaction that requires electrical energy and oxygen. Thus to determine the maintenance needed or to determine the life span of a structure it is essential to define the rate of these two factors.

Usually, reinforcement corrosion occurs as a result of the reaction between the atmospheric carbon dioxide and moisture. With rain on a concrete structure a dilute Carbonic acid reacts with the alkaline calcium hydroxide in the cement paste, forming calcium carbonate. This reduces the pH value to about 9.5, whereon corrosion succeeds if the electrical conditions are met and oxygen is available.

The thickness and density of the concrete cover to reinforcing steel is very important, as the reaction will perform more quickly in areas where the concrete cover is small. Moisture content directly effects the resistively of the concrete environment around its steel bars. In another words, as the moisture content rises, the resistively falls and the corrosion currents flow easily, thus the corrosion rate is higher.

2.2.4.1 Electrical potential

Corrosion of steel involves the movement of ions i.e. negative charges. The difference in electrical potential in the reinforced concrete structures is thus a good indication of the concrete condition, as it can determine whether the concrete is or is not being affected by the environment surrounding the structure. The so-called Half-Cell, with the aid of an interpretative table, is one way for investigating these differences in electrical potential.

2.2.4.2 Resistivity

This is complementary to 'electrical potential'. Resistivity is easy to measure in different ways. The usual way is to apply a voltage drop between two fixed points on the concrete surface and measure the resulting electrical potential between two intermediate points. This is an active method, whereas the half cell is a passive method.

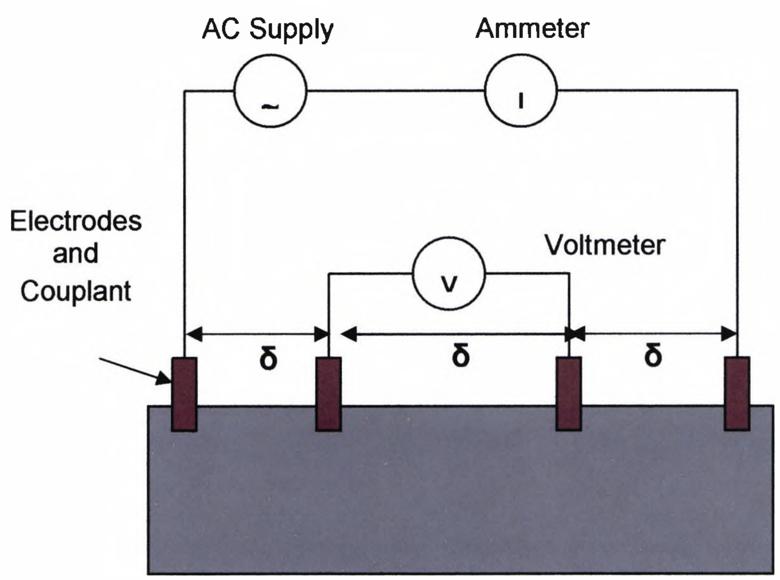


Figure (2.1) Typical Layout of the Four-Probe Technique

The most common technique is the four-probe or Wenner array figure (2.1). Test equipment is available commercially. The test can be carried out rapidly and easily with little or no damage to the concrete surface.

Methods used to detect corrosion factors are covered in the following chapter,

2.2.5 General influences

Whilst environmental actions tend to dominate the condition of concrete with time, other factors are worth mentioning. These include concrete strength, density, porosity, adverse material content, reinforcing detailing and the quality of the construction process.

2.2.5.1 Reinforcement cover

Depending on the age and exposure environment, the depth of concrete cover to the reinforcing steel is a useful predictor of the likely overall structural condition. Where cover is small, say less than 20mm in relatively normal conditions of exposure, problems can be expected with the steel reinforcement after 10 years or more, for example. This is because the environment can degrade the concrete quality between the surface of the structure and the steel bars, which is meant to provide protection to the steel reinforcement. Whilst a large amount of cover is no guarantee of concrete well-being, it is the best line of defence for the reinforcement.

The protection cover can be lost if the concrete around the steel carbonates, or chlorides (commonly sodium chloride from seawater or de-icing salts) penetrate from the surface. Measuring the cover to reinforcement is a fundamental activity in condition survey.

The thickness of cover to reinforcement is an important factor controlling the transport of chlorides ions: the greater the cover the longer the time interval before the chloride ion concentration at the surface of the steel reaches the threshold value. Thus the quality of the concrete (in terms of its low penetrability) and the thickness of cover work together and can, therefore, to some extent, be traded off one against each other. For this reason, standards often specify combinations of cover and strength of concrete, such that a lower thickness of cover requires a higher strength, and vice versa.

However, there are limitations to this approach. First of all, thick cover is of no avail if the concrete is highly penetrable. Moreover, the purpose of cover is not only to provide protection to the reinforcement, but also to ensure composite structural action of steel and concrete, and in some cases, to provide fire protection or resistance to abrasion. Unduly large thickness of cover would result in the presence of a considerable volume of concrete devoid of reinforcement. And yet, the presence of steel is required to control shrinkage and thermal stresses, and to prevent cracking due to those stresses. Were cracking to occur, the; large thickness of cover would be prove to be detrimental. In practical terms, the cover thickness should not exceed 80 to 100 mm (3 to 4 in.) but the decision on cover forms part of structural design.

Too small a thickness of cover should not be used either because, however low the penetrability of the concrete, cracking, for whatever reason, or local damage or misplaced reinforcement can result in a situation where chloride ions can rapidly be transported to the surface of the steel. [F. Rendell, 2002]]

2.2.5.2 Carbonation

Whereas steel corrosion is associated with an essentially acid environment, the fresh concrete that surrounds it is highly alkaline. Corrosion thus tends to be prohibited because there is an excess of this alkalinity. Unfortunately, atmospheric CO2 (causing so-called ‘acid rain’) acts on the exposed face of a concrete member, progressively pacifying it (reducing its alkalinity). This is called ‘carbonation’. With time, the carbonation front progresses deeper into the concrete. When it is near the depth of the cover, i.e. in the vicinity of the reinforcing bars, the lost alkalinity means that corrosion can freely occur. This usually occurs when the concrete is in an environment with a relative humidity of 50-70% or in wetting and drying conditions.

Measuring the carbonation depth (using phenolphyline) gives a rapid approximation depth of the fully progressed Carbonation. Thus it can help in assessing the corrosion risk to the reinforcing steel.

Carbonation per se does not cause deterioration of concrete but it has important effects. One of these is carbonation shrinkage. With respect to durability, the importance of carbonation lies in the fact that it reduces the pH of the pore water in hardened Portland cement paste from between 12.6 to 13.5 to a value of about 9. When all Ca(OH)2 has become carbonated, the value of pH is reduced to 8.3. The significance of the lowering of the pH is as follows.

Steel embedded in hydrating cement paste rapidly forms a thin passive layer of oxide which strongly adheres to the underlying steel and gives it complete protection from reaction with oxygen and water, that is from formation of rust or corrosion. This state of steel is known as passivation. Maintenance of passivation is conditional on an adequately high pH of the pore water. Where lower pH pore water reaches the vicinity of the surface of the steel, the protective oxide film is removed and corrosion can take place, provided oxygen and moisture necessary for the reactions of corrosion are present. For this reason, it is important to know the depth of carbonation and specifically whether the carbonation front has reached the surface of the embedded steel. In fact, because of the presence of coarse aggregate, the 'front' does not advance as a perfectly straight line. It might also be noted that, if cracks are present, CO2 can ingress through them so that the 'front' advances locally from the penetrated cracks. In many cases, corrosion can take place even when the full carbonation front is still a few millimetres away from the surface of the steel if partial carbonation has taken place. [A. Neville, 1995]

2.2.5.3 Chloride and chemical attack

Chloride contamination is well known as one of the very important kinds of contaminant for concrete. Its presence is common mostly because of the practice of applying winter salt to roads and highways. Marine structures are similarly affected. In rare cases, especially in older structures, there are occurrences of 'cast-in' chlorides, derived from additives to the initial concrete mix (to control the setting time, for example). In similar cases, aggregates were brought from the sea bed to build, dams, bridges and pipes are especially at chemical attack risk.

Chlorides do not reduce the background pH, but give a mechanism by which the protective oxide layer is maintained. In concrete uncontaminated by chlorides, the oxide layer undergoes a continual process of breakdown and immediate replenishment. Chlorides penetrate concrete most rapidly in basically dry environment where the concrete is occasionally wet. Chlorides may be present in the concrete from the time of casting if they were added to the mix either as an admixture or accidentally as a contaminant of one of the mix constituents

The presence of chlorides is important because their presence supports the migration of ions in the concrete. Free chloride ions in concrete increase the risk of corrosion. There is a field test for chloride content but it is not as accurate as laboratory-based testing. It involves taking samples and it this partially destructive.

Chloride attack is distinct in that the primary action is the corrosion of steel reinforcement, and it is only as consequence of this corrosion that the surrounding concrete is damaged. Corrosion of reinforcement is one of the major causes of deterioration of reinforced concrete structures in many locations. Nevertheless, a brief description of the mechanism of chloride-induced corrosion will be helpful in understanding the processes involved. [A. Neville, 1995]

2.2.5.4 Mechanism of chloride-induced corrosion

When a difference in electrical potential along the steel in concrete exists, an electrochemical cell is set up: there form anodic and cathodic regions, connected by the electrolyte in the form of the pore water in the hardened cement paste. The positively charged ferrous ions at the anode pass into solution while the negatively charged free electrons pass through the steel into the cathode where they are absorbed by the constituents of the electrolyte and combine with water and oxygen to form hydroxyl ions. These travel through the electrolyte and combine with the ferrous ions to form ferric hydroxide which is converted by further oxidation to rust.

In the reaction, oxygen is consumed and water is regenerated but it is needed for the process to continue. Thus, there is no corrosion in, dry concrete, probably below a relative humidity of 60 per cent; nor is there corrosion in concrete fully immersed in water, except when water can entrain air, for example, by wave action. The optimum relative humidity for corrosion is 70 to 80 per cent. At higher relative humidity, the diffusion of oxygen through the concrete is considerably reduced.

For corrosion to be initiated, the passivity layer must be penetrated. Chloride ions activate the surface of the steel to form an anode, the passivated surface being the cathode. The reactions involved are as follows:

$$Fe^{++} + 2Cl^{-} \rightarrow FeCl_2$$

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl$$

Thus, Cl^- is regenerated so that the rust contains no chloride, although ferrous chloride is formed at the intermediate stage.

The electrical resistivity of concrete is greatly influenced by its moisture content, by the ionic composition of the pore water, and by the continuity of the pore system in the hardened cement paste. [A. Neville, 1995]

2.2.5.5 Acid attack on concrete

Concrete is generally well resistant to chemical attack, provided an appropriate mix is used and it is properly compacted. There are, however, some exceptions.

First of all, concrete containing Portland cement, being highly alkaline, is not resistant to attack by strong acid or compounds which may convert to acids. Consequently, unless protected, concrete should not be used when this form of attack may occur.

Generally speaking, chemical attack of concrete occurs by way of decomposition of the products of hydration and formation of new compounds which, if soluble, may be leached out and, if not soluble, may be disruptive in situ. The attacking compounds must be in solution. The most vulnerable cement hydrate is $Ca(OH)_2$, but C-S-H can also be attacked. Calcareous aggregates are also vulnerable.

Concrete is also attacked by water containing free CO_2, such as moor land water or mineral water, which may also contain hydrogen sulphide. [A. Neville, 1995]

2.2.5.6 Disruption by alkali-silica reaction

This reaction can be disruptive and manifest itself as cracking. The crack width can range from 0.1 mm to as much as 10 mm in extreme cases. These cracks are rarely more than 25 mm, or at most 50 mm, deep. Hence, in most cases, the alkali-silica reaction adversely affects the appearance and serviceability of a structure, rather than its integrity; in particular, the compressive strength of concrete in the direction of the applied stress is not greatly affected.

The pattern of surface cracking induced by alkali-silica reaction is irregular, somewhat reminiscent of a huge spider's web. However, the pattern is not necessarily distinguishable from that caused by sulphate attack or by freezing and thawing, or even by severe plastic shrinkage.

If the sole source of alkalis in concrete is Portland cement, then limiting the alkali content in the cement would prevent the occurrence of deleterious reactions. [A. Neville, 1995]

Some types of aggregates, such as silicates, react with excess alkalis in the cement past. The expansive gel that is formed from this reaction produces a pressure that can create cracks in the concrete.

Petrography examination of a cored or sawn sample of the material is necessary for laboratory examination. However, in visual, on-site investigations, the results of attack can give a distinctive crazing pattern on the concrete surface.

2.2.5.7 Sulphates attack on concrete

Solid salt does not attack concrete but, when present in solution, they can react with hydrated cement paste. Particularly common are sulphates of sodium, potassium, magnesium, and calcium which occur in soil or groundwater. Because the solubility of calcium sulphate is low, groundwater with high sulphate content contains the other sulphates as well as calcium sulphate. The significance of this lies in the fact that those other sulphates react with the various products of hydration of cement and not only with $Ca(OH)2$. In another words, sulphates can attack concrete in a similar way as the alkali aggregate reaction, or it can attack directly the reinforcing steel. It can be visually detected by an expert inspector in the field, but laboratory testing is required for confirmation. [A. Neville, 1995]

2.2.5.8 Effects of sea water on concrete

Concrete exposed to sea water can be subject to various chemical and physical actions. These include chemical attack, chloride-induced corrosion of steel reinforcement, freeze-thaw attack, salt weathering, and abrasion by sand in suspension and by ice. The presence and intensity of these various forms of attack depend on the location of the concrete with respect to the sea level.

Chemical actions of sea water on concrete arises from the fact that sea water contains a number of dissolved salts.

The pH of sea water varies between 7.5 and 8.4, the average value in equilibrium with atmospheric CO2 being 8.2. Ingress of sea water into concrete per se does not significantly lower the pH of pore water in hardened cement paste: the lowest value reported is 12.0. The presence of a large quantity of sulphate in sea water could lead to the expectation of sulphate attack.

Wetting and drying represents much more sever conditions because a build-up of salt within the concrete can occur in consequence of the ingress of sea water, followed by evaporation of pure water, with the salt left behind. The most damaging effect of sea water on concrete structure arises from the action of chlorides on the steel reinforcement. [A. Neville, 1995]

2.2.5.9 Salt weathering

When concrete is repeatedly wetted by sea water, with alternating periods of drying during which pure water evaporates, some of the salts dissolved in sea water are left behind in the form of crystals, mainly sulphates. These crystals re-hydrate and grow upon subsequent wetting, and thereby exert an expansive force on the surrounding hardened cement paste. Such progressive surface weathering, known as salt weathering, occurs in particular when the temperature is high and evaporation is strong, so that drying occurs rapidly in the pores over some depth from the surface. Intermittently wetted surfaces are vulnerable; these being surfaces of the concrete in the tidal zone and in the splash zone. Horizontal or inclined surfaces are particularly prone to salt weathering, and so are surfaces wetted repeatedly but not at short intervals so that thorough drying can take place.

Salt water can also rise by sorption, that is, by capillary action; evaporation of pure water from the surface leaves behind salt crystals which, when re-wetted, can cause disruption.

Salt weathering can occur not only in consequence of direct spray by the sea water, but also when air-borne salt which has been deposited on the surface of the concrete becomes dissolved by dew followed by evaporation. Such behaviour has been observed in desert areas, where the large temperature drop in the small hours of the night reduces the relative humidity of the air to the point where condensation in the form of dew occurs.

Salt weathering can extend to a depth of several millimetres: hardened cement paste and the embedded fine aggregate particles are removed, leaving behind protruding coarse aggregate particles. With time, these particles can become loosened, thereby exposing more hardened cement paste which, in turn, becomes liable to salt weathering. The process is, in essence, similar to the salt weathering of porous rocks. [A. Neville, 1995]

2.3 Points of detection

An objective of this work is to enable a site based tool for interpretation of NDT data. On this basis, aspects that require laboratory intervention are excluded. For durability, the main issues are accepted as;

- The depth of carbonation related to the cover to the reinforcement.
- The electrical action associated with corrosion of the steel reinforcement.
- The actual provision of steel reinforcement in terms of diameter and spacing.
- The apparent insitu strength of the concrete.

2.4 Conclusions

The prime agents for concrete decay have been reviewed. It this research, reinforcement content, concrete cover, strength and electrical potential (half-cell potential) have been adopted as the main sources of data. This reflects their universally accepted importance in everyday site investigation work. In the next chapter the associated NDT methods are reviewed.

Chapter 3

NON DESTRUCTIVE TESTING METHODS

3 NON DESTRUCTIVE TESTING METHODS

3.1 Introduction

The purpose of this chapter is to examine the NDT methods related to the physical deterioration characteristics identified in the previous chapter. A wide range of techniques are available that measure physical characteristics associated with condition and defects. However, this chapter concentrates mostly on the methods that have been adopted to provide data for the subsequent data fusion experiments. The reason behind using different types of NDT methods is because of the various kinds of defects concrete can have and the way in which knowledge of these combines to enable judgement of condition. In the research, the choice is largely influenced by the NDT equipment that was made available to the researcher. Fortunately, these are commonly used devises.

3.2 Preliminary Considerations

Many investigations are initiated because a routine inspection has revealed a defect. As it was suggested in figure (3.1), investigations are also initiated because deterioration has accelerated or because an obvious fault has developed. Among the common reasons for carrying out investigations are the following [F. Hills, 2000] and [J. B. Menzies, 2001]:

- A defect or form of deterioration has been noticed e.g. cracking, spalling or erosion of the surface.
- Structural weakness or distress is apparent. Typical signs are large deflections or cracking.
- General or local damage has occurred and some form of defect is suspected.

Defects as often discover during routine maintenance programmes, .where change of use of the structural is planned or changing of the ownership is to occur.

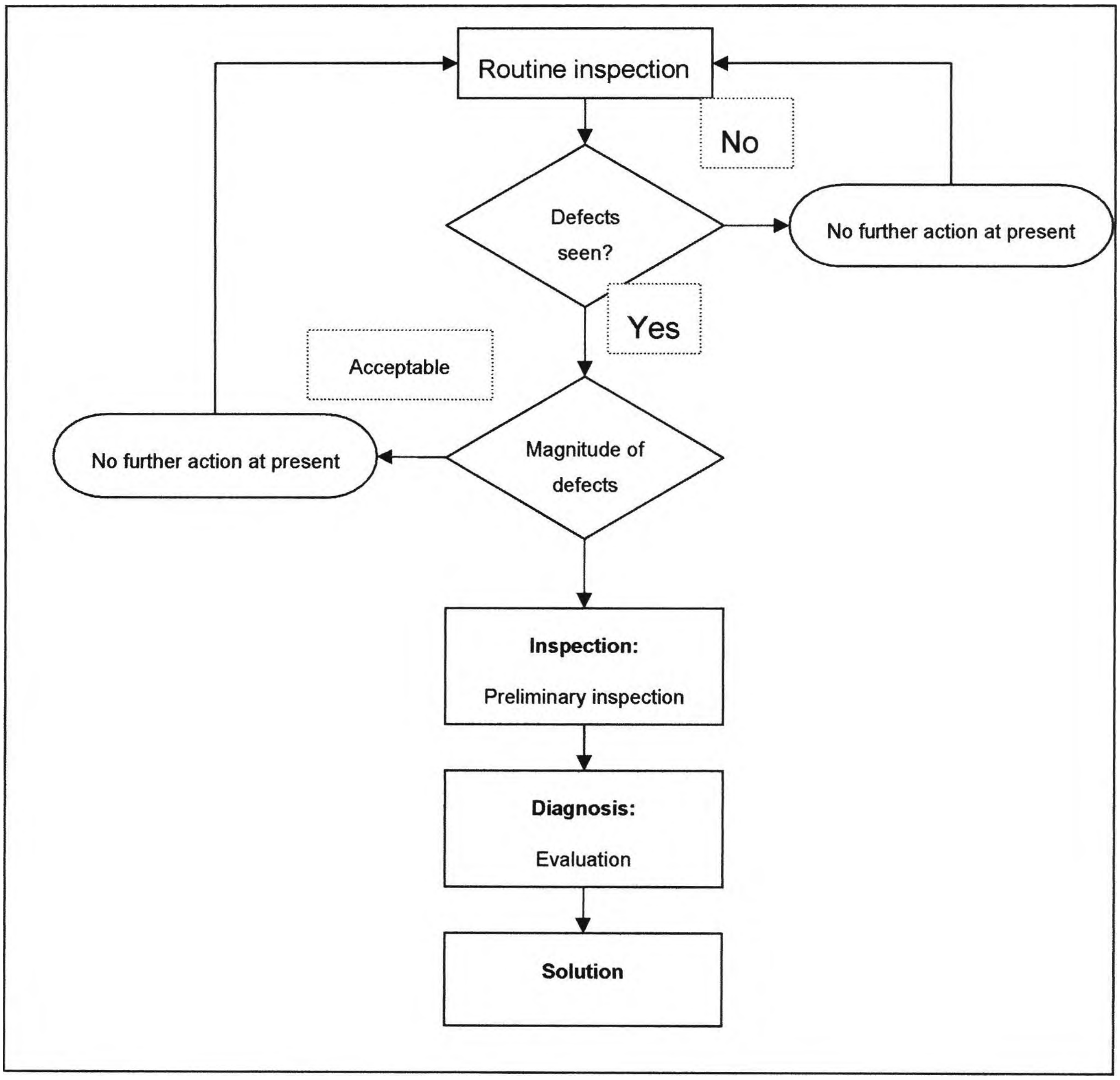


Figure (3.1) Flow Chart- from routine inspection to solution

3.3 Non Destructive Testing

To assess any reinforced concrete structure, three key conditions have to be evaluated. These are;

- The overall integrity and quality of the concrete.
- The existence or risk of corrosion of the reinforcing steel.
- The possible presence of contaminants or other agents that may directly attack concrete, causing extensive or disruptive reactions.

An explanation of the NDT methods selected and there relevance is given in the following sections.

3.3.1 Schmidt Hammer

The need to determine an estimate of insitu strength is clear in survey work and assessment. To this end, the Schmidt Hammer is a powerful instrument for measuring the surface hardness and indirect strength in a non-destructive way. It is also called the Impact Hammer, Accelerometer, or the concrete test hammer. E. Schmidt first designed it in 1948 for carrying out in situ tests on concrete.

The Schmidt hammer is portable, light, and useful for insitu testing, and it is cost effective too. It records the rebound of a spring-loaded mass, which depends upon the elastic recovery of the surface and thus its hardness and compressive strength. Schmidt hammer is widely used in other fields like rock mechanics and earth works engineering.

The most commonly used Schmidt hammers are type L and type N. Type L has an impact energy of 0.735 N.m, and type N 2.207 N.m. Other than these two types, there are types M and P. In this research a digital version of the type N is used.

3.3.1.1 Hardness and compressive strength

With rebound hammers, strength is measured indirectly on the basis that strength and hardness go together. The actual measurement is the rebound number, R. There is a calibration curve for each instrument provided by the manufacturer, giving both compressive strength and "R" values. Using 12 rock samples.[A.Singer, 1999] and [H. Yaalon, 2001], found the following relation between "R" values and the compressive strength:

$$(\text{Log}\ (\delta/\ (9.81*104)))= (0.0387R+0.826)$$

Where δ is the compressive strength in N/m^2 and R is the measured rebound number.

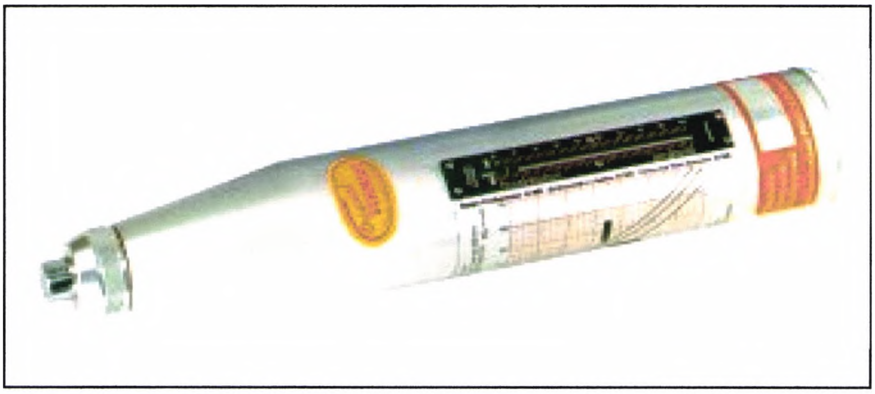


Figure (3.2) Schmidt Hammer

3.3.1.2 DIGI Schmidt

Rebound hammers are available with either analogue or digital output. The adopted Digi Schmidt hammer, illustrated in figure (3.3), outputs directly a strength value. It has the advantage over analogue versions in giving the strength of the tested concrete as a result of statistical processing of a series of individual impacts. It also allows the user to compensate for direction of impact and the type of hardness-strength relationship to be operated. It can be interfaced to further analysis, if required. The compressive strength accuracy of measurements is +/- 0.2 R and reproducibility of +/- 0.5 R. However, it has been well establish that the accuracy in strength measurement can be in error by 30-40 %. Readings are affected by the presence of aggregate stones, the type cement, water and moisture content, for example. The value of the method is in a relative sense, comparing different locations within a structure rather than placing great emphasis on absolute values.

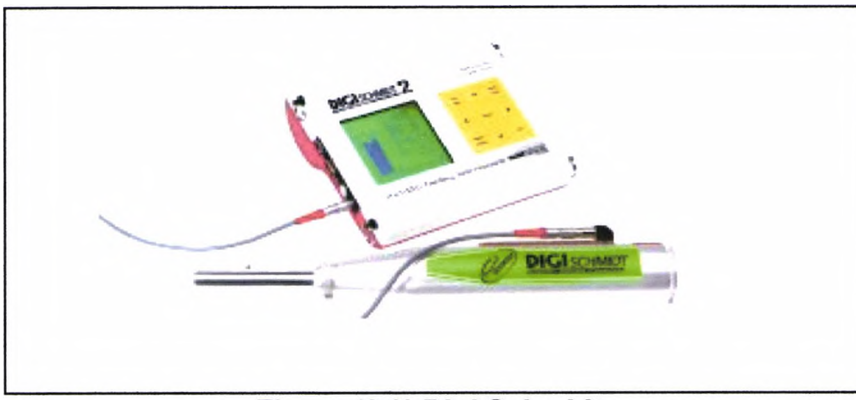


Figure (3.3) Digi Schmidt

3.3.1.3 DIGI-Schmidt 2000

The Rebound Hammer DIGI-SCHMIDT 2000, which has an electronic display unit, is mainly suitable for systematic and extensive measurement. This relates surface hardness to concrete strength. Various parameters such as impact direction, calibration, depth of carbonisation can be set. Extensive display, evaluation and storage of data, as well transmission to a printer or PC, are possible.

Figure (3.4) DIGI-Schmidt 2000

3.3.2 Covermeter

Steel can be detected by passing an electro-magnet over it. The strength of detection depends on the following factors

- Principal direction of the steel object in relation to the direction of the field.
- Actual mass of steel present.
- Distance of the steel object from the centre of the flux field.

With a suitably precise instrument, properties can be worked thus to allow direction, depth and size determination.

The covermeter, as illustrated in figure (3.5) is a very useful instrument in inspections. It enables estimates of the depth and cover to the reinforcing bar and its size or diameter. Size determination is rather less accurate than cover because the bar depth detection is rather insensitive to bar size. It is quite accurate for shallow concrete covers. Its detection range is 0-125 mm and the depth accuracy about +/- 2 mm. Generally speaking, reinforcement is estimated to the nearest diameter size.

Figure (3.5) CM52 Covermeter

The version of the covermeter which is called (CM52) as shown in figure (3.5) is a very useful as it can detect and give the size of the bars in a single operation. The range of detection can increase if the optional head is used to 200 mm.

There other Covermeters available in market now with better features and easier to use, and most important fact is that these Covermeters are much faster in achieving the results required which in the other hand is saving valuable time and money. The new CM9 Microprocessor CoverMaster is as shown in figure (3.6).

Figure (3.6) CM9 Microprocessor CoverMaster

3.3.2.1 Protometer 5 Rebar Detector

The PROTOMETER 5 rebar locator is used for detecting reinforcing bars and welded wire meshes as well as measuring concrete cover. Bar diameters can be assessed. Especially designed software, facilities calculations and data transfer to a PC

Figure (3.8) PROTOMETER 5 Rebar Detector

3.3.3 TICO Ultrasound

The TICO Ultrasound unit is used for detecting the sub-surface properties of concrete. Ultrasound gives a way of investigating concrete properties such as uniformity, cavities, and cracks, defects due to fire and frost as well as indirect determination of the modulus of elasticity. Use of this equipment is advantageous because it can be set up to give a specific data block, which helps in the input for fusion. With the measuring of the transmission time and calculation of the pulse velocity, the device has large display data evaluation and storage as well as transfer to a printer or PC is possible.

Figure (3.7) TICO ULTRASOUND

3.3.4 Canin Corrosion Detector

The CANIN detector is a corrosion analysing instrument that determines the corrosion potential of reinforcing bars. It uses the fact that corrosion of steel in concrete is an electrochemical process. This represents a galvanic element similar to battery, producing an electric current measurable as an electric field on the surface on the concrete. The instrument can make a large area assessment directly to memory using intelligent memory rendering (unique worldwide instrument). This means that the display resolution reflects the density of data. Over 100,000 data items can be stored for transfer to a printer or PC.

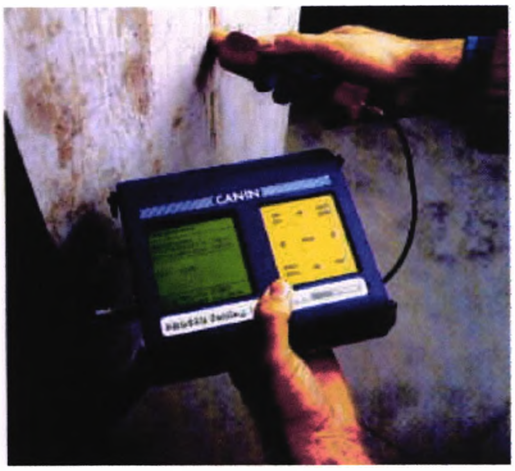


Figure (3.9) CANIN Corrosion Detector

3.3.5 Resistivity

When reinforcement corrodes, an acidic environment exists in which ions can freely move through the reinforced concrete. Whereas concrete would normally be an insulator material (high resistance) it becomes conducting. Thus, if a modest voltage is applied between two fixed points on the surface of such concrete, an electrical current can be detected in the zone between these points. A low resistivity is thus apparent, depending on the intensity of corrosion activity. The lower the resistivity value the more intense the corrosion activity and visa versa.

The adopted device is a 4 probe Wenner Array. This determines the resistance (ohm cm) of the concrete by delivering a 30 v AC voltage across the outer contact points. The type of device used delivers a liquid couplant by a pumping action on the surface. Table (3.1) gives interpretations for the likelihood of corrosion.

Resistivity (ohm cm)	Interpretation
Greater than 100,000 to 20,000	Corrosion extremely unlikely
20,000 to 12,000	Corrosion unlikely
12,000 to 8,000	Corrosion probable
8,000 to 000	Corrosion almost certain

Table (3.1): Resistivity Indicators

3.3.5.1 RESI Resistivity Meter

The RESI resistivity meter is used for measuring the electrical potential field for determining the corrosion rate of reinforcing bars in the concrete. Furthermore, the influence of various concrete components on the electrical resistance can be investigated. The electrical resistance is measured according to the Wenner four points method. The measuring data can be either stored in form of single grid or transferred to a PC.

Figure (3.10) Resi Resistivity Meter

3.3.6 Half Cell

As with the previous method, this method is an attempt to measure the level of corrosion activity. The half cell measures the drop in voltage between two probes. It can be used in different ways, absolute and relative. In the first method one terminal is connected to the steel reinforcement and the other tested at different locations on the surface. A drill hole is made at the location of a bar and the electrode attached. Good continuity of the reinforcement is needed throughout the area tested.

Success with the method depends on continuity of the reinforcement. Readings are affected by moisture at or near the concrete surface. Equipment has optional reference cells, copper/copper or silver/copper. The equipment used was of the latter type. Table (3.2) gives an interpretation of the readings.

Copper/copper Sulphate Electrode	Silver/silver chloride Electrode	% chance of corrosion active steel
(mV Vs CSE)	(mV Vs Ag/AgCl/ sat Cl)	
-500 to -350	-410 to -260	95%
-350 to –200	-260 to –110	50%
-200 to – 000	-110 to 000	5 %

Table (3.2): Half Cell Potential Indicators

3.3.7 TORRENT Permeability Tester

The TORRENT permeability tester allows the durability of concrete structures to be evaluated, especially in cases of high strength concrete. During operation, the instrument is placed on the concrete surface within a vacuum cell. The loss in vacuum i.e. the increase in pressure inside the cell relates to the degree of permeability of the concrete (permeable concrete allows air through); an important characteristic is the outer chamber of the cell that protects from lateral air streams and gives high accuracy in measurement. The stored measuring data can be directly printed by means of a printer or transferred to a PC.

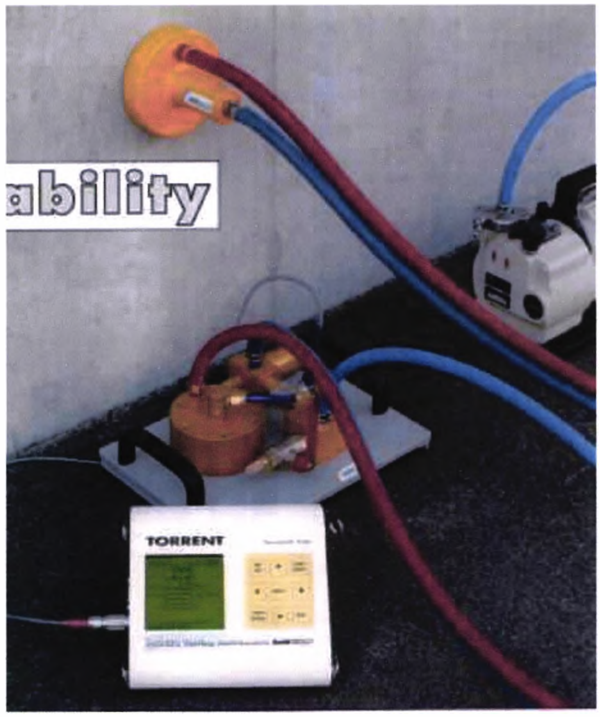


Figure (3.11) TORRENT Permeability Tester

3.3.8 Impact Echo

As described previously in Concrete Quality and Integrity, test methods based on this principle generally fall into four categories, all of which use some from data acquisition system to record the signals from the transducers. These are P-Wave, Acoustic, Ultrasonic, and Nuclear.

In the case of Impact-Echo- the surface is instrumented with a sensitive displacement transducer, and a high frequency range (20-40 KHz) P-wave is generated by an impact from a small steel ball. The signal from the displacement transducer is analysed in the frequency domain, rather than as a time-based signal. Used where the wave path length will be less than about two meters, to locate flaws and discontinuities. It is ideal for locating small voids and delimitations near the surface. [H. Bernard, 1998]

3.3.8.1 IE Test Method: General description,

As stated, the IE method has been performed on a point-by-point basis by hitting the test surface at a given location with a small instrumented impulse hammer or impactor and recording the reflected wave energy with a displacement or accelerometer receiver mounted to the test surface adjacent to the impact location, as illustrated in figure (3.12), Since the reflections are more easily identified in the frequency domain, the time domain test data of the impulse hammer (if measured) and receiver are processed by a signal analyser for frequency domain analyses. For data collected with the impulse hammer and accelerometer, a transfer function, (system output/input) is then computed between the hammer (input) and receiver (output) in displacement units as a function of frequency. If all impactor is used instead of an instrumented hammer, then just the linear spectrum of the receiver signal is computed and displayed. Pronounced 'echo' peaks in the transfer function or frequency spectrum test records, of the compression wave energy indicate reflections, or 'echoes'. These peaks correspond to thickness or flaw depth resonant frequencies. If the velocity of the concrete is known or can he measured (as is usually the case), then, the depth of a reflector can be calculated from the echo peak frequency. For sound concrete slabs or walls, the depth of the reflector will correspond to the local slab or wall thickness.

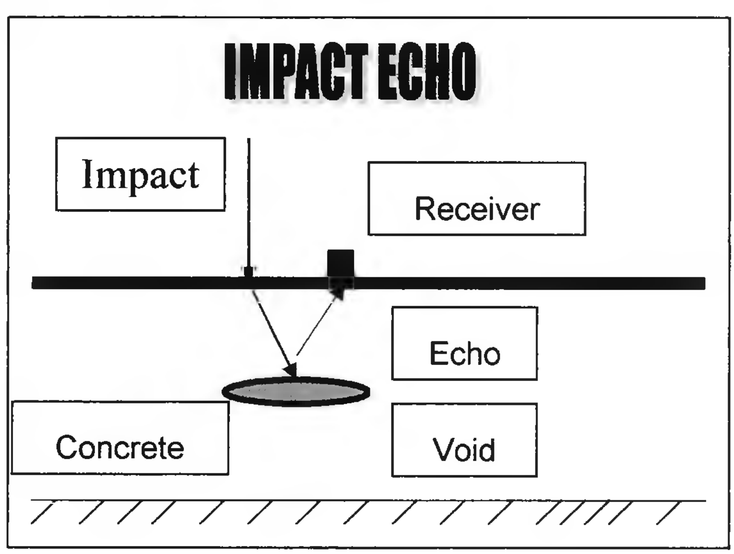


Figure (3.12) Illustration of Impact Echo's Function

3.4 Other NDT methods

There are a number of advanced NDT methods that take advantage of the propagation of elastic waves through concrete, which is a function of the density and elastic modules of the material. For this reason the quality and the condition of the concrete can be estimated by determining the time that these waves travel in a knowing distance. By determining the time waves through a knowing distance in a different location of a structure and then compared the uniformity of the concrete can be assessed. Methods that apply these characteristic are:

- Impulse-Echo, Impact-Echo-Impulse, High resolution ground penetrating radar and Response Spectrum (P Wave)
- Ultrasonic Pulse Velocity and Cross hole Sonic Logging (Ultrasound)
- Gamma / Gamma Logging (Nuclear). [.E. Gros, 1997]

The use of ultrasound in the form of the 'Pundit System' is made in surveys where the dimensions of the concrete member can be measured. This is difficult, however, because of the need to achieve a coupling with the concrete (often very uneven and rough). The others are more experimental and developmental systems. In the context of reinforced concrete examination, Radar only works provided there is adequate spacing between the reinforcing bars. When appropriate, it can also give information on voids, cracks and other defects in the concrete. This 'other' NDT equipment was not available to the researcher and thus is not included in the data fusion modelling. They could be considered, however, in future development, beyond the reported research

DEVICE	RAW DATA	INDIRECT DATA	SIGNIFICANCE	COMMENT
Pull-Off	Force	Tensile Strength/Bonding Strength	Indicates surface bond strength	Only tests small area. Good for testing patch repair.
Windsor Probe	Length	Strength	Resistance to Penetration	Partially destructive
Schmitt Hammer	Rebound Number	Elastic Stiffness	Relates to Strength	Manual or Digital Device Available
Half Cell	Voltage (Potential Difference)	Strength of acidity in concrete	Indicates corrosive environment to rebars	Can be used absolutely or relatively (Affected by water content)
Resistivity	Voltage	Impedance Indicating Ease of Ion Migration	Indicates Corrosive Environment for Steel Reinforcement	Can be used as absolute or Relative Way (Affected by Water Content i.e. Wet/Dry
Covermeter (Metal detector)	Voltage	(i) Bar Centre & Direction (ii) Bar Diameter (iii) Bar Depth (Cover)	Relates to Strength & Durability of Structure	Voltage or Digital Available
Radar	Image	(i) Voids Location & Size (ii) Presence of Steel (iii) Material Properties (Dielectric K)	Indicates Changes in Material Properties With Depth.	Requires Considerable Expertise for Interpretation
Manual Hammer	Noise (Hollow Sound)	Presence of Delimitations	Durability of Structure	Could be used as acoustic capture System
Pundit Pulse Velocity (Ultrasound)	Time of Flight Spectrum.	Depths of Reflecting Features & Variation in Bulk Modulus.	Indicates Depths of Interfaces, such as voids	Requires good acoustic coupling
Impact Echo	Time of Flight From Discrete Impact	Depths of Reflecting Features & Variation in Bulk Modulus.	Indicates Depths of Interfaces, Such as Voids.	Largely Experimental
Gas Permeabilit y	Pressure Loss	Porosity	Voids: Indicating Water/Cement Ratio	Partially Destructive

Table (3.3) A Summary of NDT

3.5 Conclusion

In term of NDT methods and equipment, different features and specifications have been considered. While it would be interesting to be able to adopt a broad range of equipment, this is neither practical nor necessary. The main point of the research is to investigate data fusion of NDT data and implement and test of the core ideas. Four different NDT methods have been adopted; half cell potential, resistivity, cover meter and rebound hammer. The data types from these are dissimilar and thus are useful in testing data fusion ideas. They are also available and represent the most commonly used NDT methods.

Chapter 4

DATA FUSION

4 DATA FUSION

4.1 Introduction

This chapter introduces the concept of data fusion and then presents a 'state of art' review of the topic in the context of the research objectives.

It is important to gather different NDT data from the tests to give a clearer picture of the condition of the structures investigated. Each method endeavours to quantify an important characteristic.

Gathering such data is time consuming and thus has high associated costs. A survey at 1% area sampling of a bridge could take several weeks, for example. It is thus very important from both the economical and technical viewpoints to maximise the value of the survey. Combining data and interpretation of individual NDT data is how the experienced surveyor forms a view on the structure in question. This is not a simple process because of the following;

- The data sensors are of different types.
- Sensors read different quantities.
- Measurement units are different for each sensor.
- Reliabilities are different.
- Each sensor has a different interpretation.

In spite of this, the expert surveyor is able to piece together his picture. To assist established surveyors and help those new to NDT, the author seeks to improve the way in which NDT data is handled, both statistically and by combination. The author proposes data fusion as a way forward to securing added value in NDT survey work.

In this chapter, the author reviews previous work in the area of data fusion. Prior to making the choice of experimental methods for implementation, various methods to fuse data are explained and advantages and disadvantages evaluated. A table giving a summary comparison is worked out (table 4.1), and the decision for the method selection explained.

4.2 Data Fusion Concept

The purpose of investigating data fusion is to give the possibility of combining different NDT data towards a condition and repair decision.

Humans operate data fusion in many aspects of daily life to provide a basis for decisions. This is done both consciously and sub-consciously, for example, in recognising another person's identity, the image and voice of that person are processed at the fusion centre, the brain. A questioning process is then applied to compare this data with that stored in memory. This incorporates a check to find out whether there are any changes in the voice or the look of the viewed person relative to previously observations. Conclusions might then follow on the identity of that person and their apparent behaviour.

The figure below illustrates human perception fusion

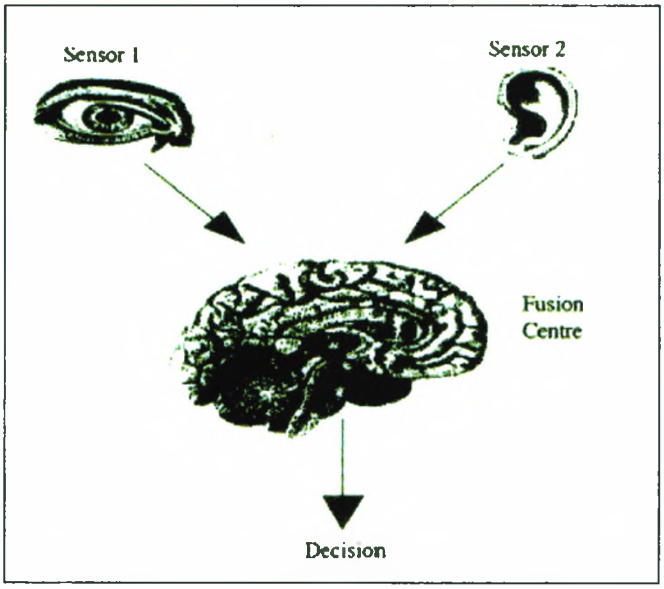


Figure (4.1) Illustration of the Human Data Fusion System

The analogy with the above is that good concrete, without decay problems is recognisable from NDT readings. Defective concrete will also be apparent by different observations using NDT equipment. The application of single NDT methods, whilst useful, is insufficient to confirm possible decay. As with the recognition of a person, data fusion can strengthen opinion on the concrete condition. If the model is correct, expert results may be possible. [E. Gros, 1997]

4.3 Data Fusion applications

Applications of data fusion span a broad range of disciplines, such as robotics, airborne, surveillance, target tracking and defence, [S. Blackman, 1988]. The most impressive data fusion implementations are in military applications, [J. Llinas, 1989] There are also other areas where data fusion is used, in pattern recognition, image analysis, fusion of satellite images and co-ordination and integration of disparate sensory information from mobile robot systems, [C.W. Tong, 1987].

4.3.1 Current and future trends:

It would be difficult to compile an exhaustive list of all current and future application of data fusion for condition monitoring and NDE. Indeed, recent research efforts have focused on improving decision support, facilitating sensor management, estimating probabilities of defect characteristics, fusing images of 3-D reconstruction and data fusion for autonomous remote inspection system.

One of the most recent industrial applications is the fusion of ultrasonic and radiographic data for improving automated defect detection in welds. The fusion algorithm is based on the Dempster-Shafer theory, and the representation of uncertainty in a colour-coded manner facilitates signal analysis. Although defects of small dimensions could be accurately detected, it was clear that false alarms could not be avoided.

European industries are working closely with research institutes to develop data fusion system that will suit specific applications. The MISTRAL project funded by the European Commission, that involves several European industrials, is aimed at the design, develop and evaluation of multi-sensor approaches to the inspection of welded components. It consists of multi-technique inspection probes, processing tools, a fracture mechanics code in conjunction with standard acceptance criteria, and fusion procedures for signals from complementary NDT techniques. [V. Just, 1998]

Another application is the detection of local non-homogeneities in composites. By using defect location determined with acoustic emission, and segmenting ultrasonic and radiograph images, Jain et al. used a fusion technique to reconstruct a complete map of the defect location and shape. [A. Jain, 1991]

The use of a neural network to perform data fusion operations is another aspect worth mentioning. Researchers in the USA used a multi-layer perceptron (MLP) and radial basis function (RBF) networks to fuse ultrasonic and eddy current information at the signal, pixel, feature or symbolic level.

Applying artificial intelligence technology to the field of NDT appears very promising, and could substitute the human operator when making impartial repair decisions.

Hannah et al. demonstrated the strategy and structures involved in making decisions based on condition data in the fields of combustion and fault diagnostics analysis. Fuzzy logic membership functions are applied in data association, with evaluation of alternative hypotheses in multiple hypothesis testing. [P. Hannah, 2000]

Stover et al. developed general purpose fuzzy-logic architecture in robotics that control sensing resources, fusion of data for tracking and automatic object recognition. [J. Stover, 1996]. Fuzzy techniques can also be used for image analysis and to reveal information of key interest to NDT operators.

Increasing applications of NDT data fusion has led to the development of new tools necessary to combine information efficiently (e.g. software, fusion architecture, and uniform data format). For example, the UNIX based CIVA software was developed for processing of eddy current, radiographic and ultrasonic data, as well as data fusion and 3-D visualisation. [P. H. Benoist, 1994]

The TRAPPIST system (Transfer, Processing and Interpretation of 3-D NDT Data in Standard Environment) was designed by European research teams to improve the accuracy of NDT signal interpretation using an automated expert system. One achievement of the TRAPPIST project was to combine radiographic and ultrasonic images to reveal the exact geometry of bore holes and to distinguish between bore holes and delamination otherwise impossible to recognise from individual images. [C. Nockemann, 1996]

With new multi-sensor techniques being developed, the use of data fusion for industrial applications will increase and the amount of information generated will have to be processed in an efficient manner.

4.4 Multisensor Data Fusion

The use of multiple sensors is essential in the investigation of any structure. Each type of sensor can test or give a different set of data that can collectively draw what is called the rich picture of the condition. This is the picture or the tool that comprises all the related factors, such as the location of steel bars, their sizes, whether there are changes in their diameters, voids and the concrete condition. In established data fusion systems, however, it is common to have multiple sensors of the same type, used for voting, for example. This is the main difference between established data fusion methods and the current research.

It is difficult to assess the condition of a structure using a single NDT method simply because structures can be affected in different ways throughout its components, as well as the multi-faceted issue. Also, depending on the actual condition of the material and the prevailing environment (e.g. dry or wet) the accuracy of individual sensing methods can be poor or marginal. Data fusion gives the chance for individual statistically weak observations to be combined into a single statistically strong conclusion. [J. L. Crowley, 1993]

There are advantages and disadvantages in using data fusion. Choosing the most appropriate fusion model is a very important issue for accuracy in the outcome and efficiency in the structural investigation. Accuracy is clearly important because investigations provide the basis for decisions on what is frequently very expensive repair work. [G. Martin, 1987]

4.5 Importance of using data fusion:

To improve the efficiency of a structural inspection, there is the need of using various numbers of NDT methods to obtain a clear vision of the present situation of that structure. Different NDT methods collect raw data describing or investigating a different characteristic of concrete condition. Fusing this data together is very important in the next stage and that is to satisfy the target aimed for in the inspection. In most cases the main goal for the inspector is to achieve knowledge of the overall condition of the structure and its probable remaining life span. This will only be possible if all characteristics are known and combined together, as most of these characteristics only have meaning when considered together. For example, if there is a defect in the reinforcement of concrete, this is likely to affect the concrete surrounding the reinforcement .For example, it may cause some cracks that reduce the structural capacity and eventually cause a complete failure.

Data collection can be a very time consuming activity. Thus, there is also an economical factor, as the inspector needs to take maximum advantage of the data collected.

4.6 Advantages and disadvantages of using multisensor data fusion:

The significant advantages that can be gained from the synergistic use of multisensor information in NDT are: -

- Increased probability of defect detection.
- Increased accuracy of defect detection.
- Improved system reliability.
- Higher order of dimensionality.
- World model visualization.

The very nature of the data fusion method, which relies on the superposition of the results of different inspection techniques, adds confidence in the results. With the provision of a suitable graphical man-machine interface, the skill needed to interpret results can be reduced. These attributes go a long way towards fulfilling the industry's requirements for unambiguous, operator-independent and easy to interpret non-destructive tests. If realised, such tools could also play a major part in training thus inexperienced in NDT and survey work.

The potential advantages in integration and/or fusing information from multiple sensors is that high level useful information can be obtained more accurately, concerning features that are perhaps impossible to perceive with individual sensors, in less time and at a lesser cost.

The main disadvantage of using data fusion is the complications that can accrue in the process of building a model. Statistics may be a way to define the targets. Thus, the model is achieved by applying statistics in the fusion model, which may complicate the calculations even further. However, the high level decision gained from this fusion model will be more accurate. [Y. Demazeau, 1993]

4.7 General fusion model

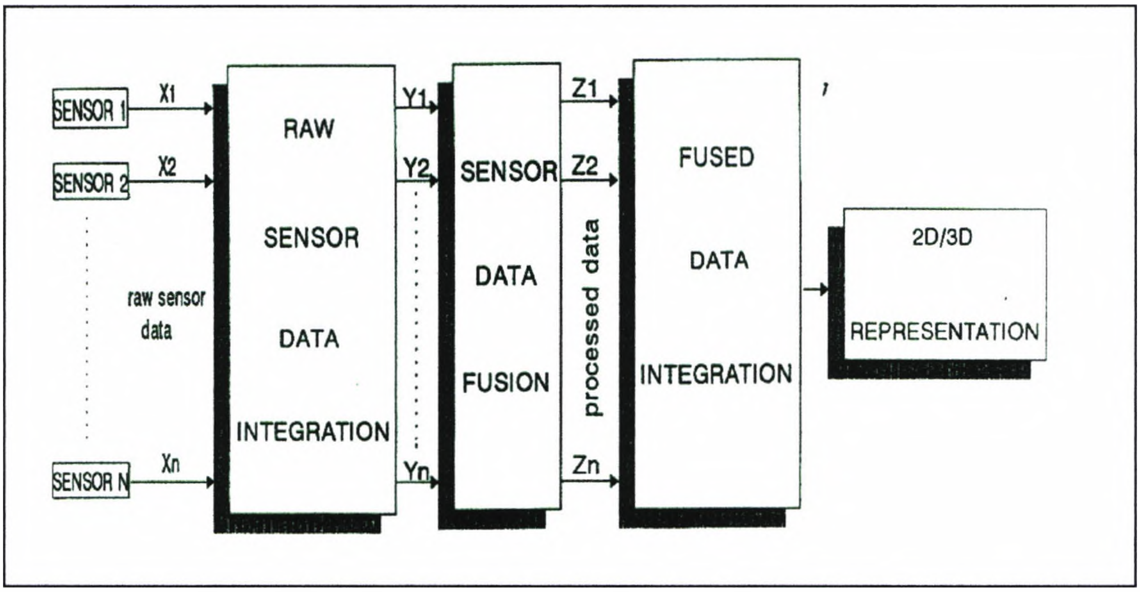


Figure (4.2) Multisensor Data Fusion (general system model)

A general system model of multisensor data fusion and integration has been worked out [H. F. Durrant-Whyte, 1988]. The signals X1, X2, from N sensors are to be integrated to provide information about the defects present in the structure. As stated previously, data integration refers to the synergistic use of the information generated by multiple NDT sensors to assist in the overall structural inspection task. Multisensor data fusion refers to any stage in the data integration process where there is an actual fusion or combination of the information from different sensors into a single representational format in order to improve data accuracy for enhanced interpretation [D. Popovic, 1992].

The principal difficulty with this approach lies in the integration of defect data from disparate inspection tasks into a world model. The actual signals are dissimilar; voltage, resistance etc., and they address different quantities; corrosion, thickness etc. In intelligent multisensor inspection system, information from NDT sensors is transformed to a common high level symbolic format suitable for incorporation in a world model.

4.8 World Models

World models are usually defined in terms of a high-level representation. The majority of the research related to the development of multi-sensor world models has been in the context of the development of suitable high-level representations for multi-sensor mobile robot navigation and control. [R. Luo, 1989]

4.8.1 The multisensor Kernel system

The multisensor Kernel system is presented as a means of representation sensor information that is compatible with the specification of logical sensors. Object features are extracted from low-level sensory data and organized into a three-dimensional "spatial proximity graph" that makes explicit the neighbourhood relations between features. Each feature is defined in terms of a logical sensor and is available to the system as the output of that logical sensor's characteristic vector. [T. Henderson, 1988]

4.8.2 The NBS sensory system

World models at each level in the hierarchy are used to create initial expectations about the form of the sensory information available at that level. They are then used to generate predictions for the task control units in the hierarchy, so that they do not have to wait for sensory processing to finish. Errors between the sensed information and the world model are used initially to register the model and later to maintain the consistency of the model during operation of the system. [M. Shneier, 1984]

4.8.3 World Model's presentation

The world model produces large amounts of data. In order to derive benefit from this data, it needs to be integrated or fused so the inspector can gain a more accurate and consistent view without increasing the complexity or the cost of the inspection activity.

The ideal technique is to generate a 3D image, which has the appearance of the structure under inspection, but also contains the fused and integrated defect information. This representation of the data in the full 3D image would make essential use of colour, with the voxels (3D pixels) coded with the defect information. Figures (4.3), (4.3), (4.5) and (4.6) illustrate how effective this representation type is.

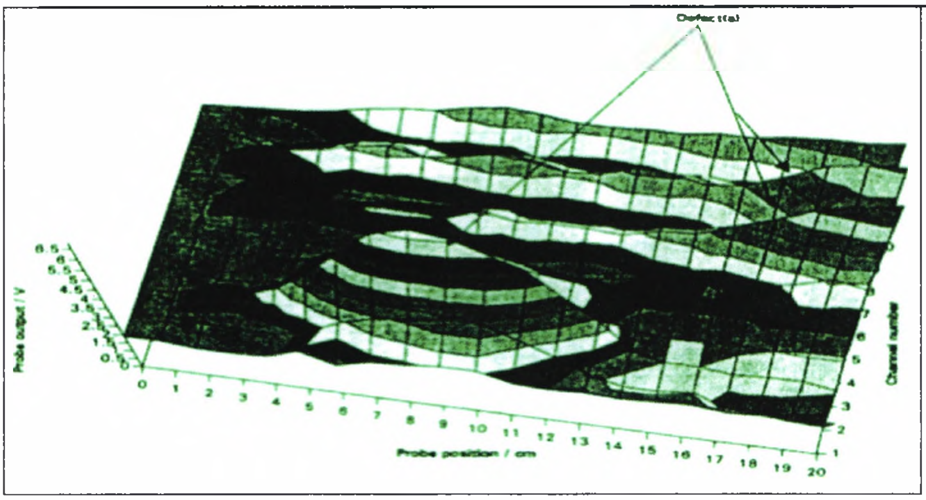


Figure (4.3) Integration of Eddy Current Data (rotor blade inspection)/Scan No 1

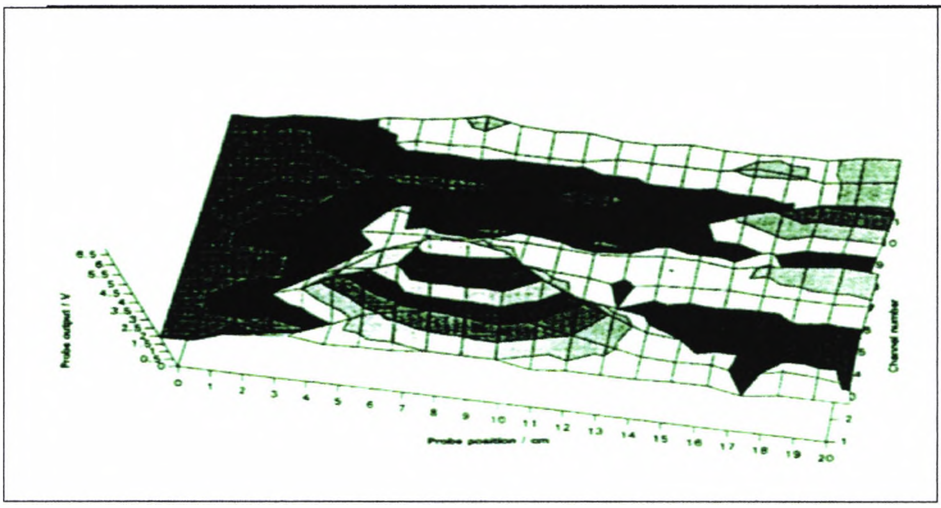


Figure (4.4) Variation of Eddy Current Signal on the Surface of the Rotor Blade Inspected/Scan No 2

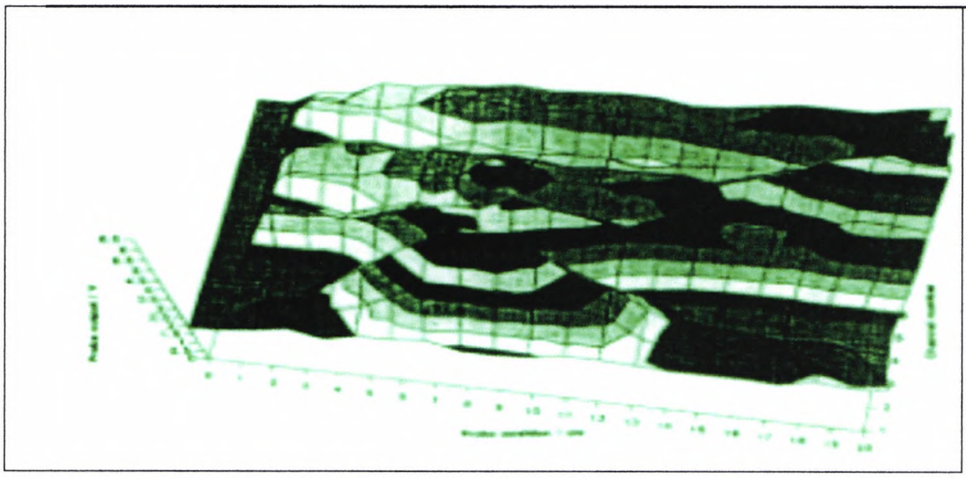


Figure (4.5) Eddy Current Data from Rotor Blade Surface Inspection/Scan No 3

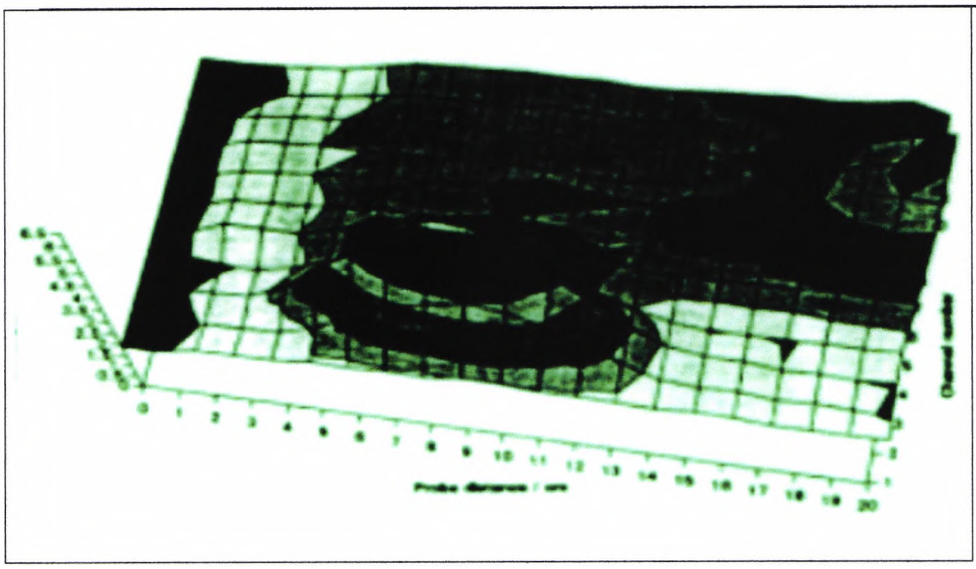


Figure (4.6) Fusion of Current Data Using Statistical Ensemble Averaging

4.8.4 4.8.4 Relevance to NDT problem

The world model approach is relevant to the NDT data fusion problem in respect to the representation of data. This is particularly so because the NDT data must be set in its spatial context. The core idea of the world model is carried through in experimental analysis tool development.

4.9 General Approaches to multi-sensor integration and fusion

Different approaches to different aspects of the multi-sensor integration and fusion will be presented as follows: -

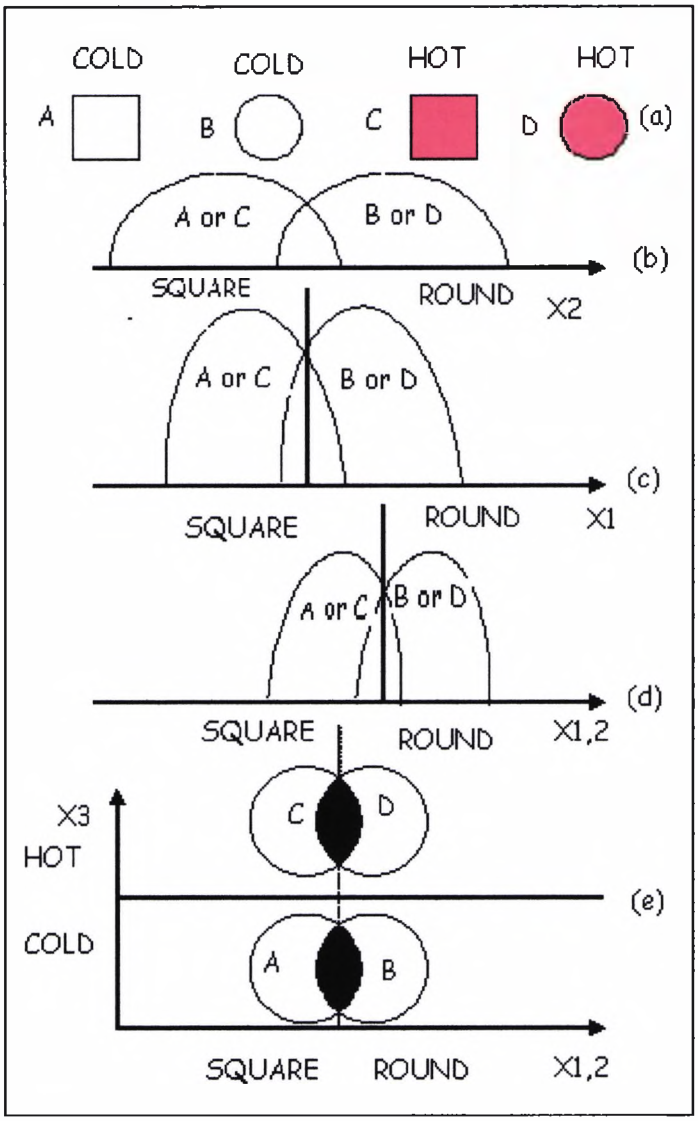


Figure (4.7) DISCRIMINATION of Four Different Objects Using Redundant and Complementary Information from Three Sensors

(a) Four objects (A, B, C, and D) distinguished by features "shape" (square vs. round) and "temperature" (hot versus cold). (b) Two-dimensional (2-D) distributions from sensor 1 (shape). (c) Sensor 2 (shape). (d) 2-D distributions resulting from fusion of redundant shape information from Sensors 1 and 2. (e) Three-dimensional (3-D) distributions resulting from fusion of complementary information from Sensors 1 and 2 (shape), and Sensor 3 (temperature).

Figure (4.8) illustrates the distinction between complementary and redundant information by using the network structure from figure (4.7) to perform, hypothetically, the task of object discrimination. Four objects are shown in figure (4.7) part (a). They are distinguished by the two independent features, shape

The uncertainty in figure (4.7) part (d) is shown as approximately half of figure (4.7) part (b & c). In figure (4.7) part (e), complementary information from Sensor 3 concerning the independent feature, temperature is fused with the shape information from Sensor 1 and 2 shown in figure (4.7) part (d). As a result of the fusion of this additional feature, it is now possible to discriminate between all four objects. [M. Fischler, 1987]

4.9.1 Paradigms and frameworks for integration

4.9.1.1 Hierarchical Phase-Template Paradigm:

Luo has proposed a general example for multisensor integration in robotic systems, this based on four distinct temporal phases in the sensory information acquisition process. This is called the Hierarchical Phase Template Paradigm. The 4 phases are "far away", "hear out", "touching", and "manipulation", and they are distinguished at each phase by the range over which sensing takes place, the subset of sensors typically required, and most importantly, the type of information required, [R. C. Luo, 1989]. This applies to situations where sensors of the same type and data value are involved, which is not the case in the current NDT problem.

4.9.1.2 Neural Networks

Neural Networks provide a fairly well established formalism with which to model the multisensor integration process. Neurones can be trained to represent sensory information and through "associative recall" complex combinations of the neurones can be activated in response to different sensory stimuli. "Simulated annealing" is one of many optional states in a network based upon the local state of activation of each neuron in the network. [C. Whittington, 1990]

[J. C. Pearson, 1988], have presented a neural network model for multisensor fusion based on the barn owl's use of visual and acoustic information for target localisation. Separate visual and acoustic maps are fused into single map (corresponding to the owl's optic tectum) which is then used for head orientation, [O. G. Jakubowicz, 1988] has presented a neural network-based multisensor system that is able to reconfigure itself adaptively in response to a and temperature. Sensor 1 and 2 provide redundant information concerning the shape of an object, and Sensor 3 provides information concerning its temperature. Figure (4.7) part (b &c) shows hypothetical frequency distributions for both square and round objects, representing each sensor's historical references to such objects. The bottom axes of both figures representing the range of possible sensors readings. The output values x1 and x2 correspond to some numerical "degree of squareness or roundness" of the object as determined by each sensor, respectively. Because Sensors 1 and 2 are not able to detect the temperature of an object, objects A and C (as well as B. and D) cannot be distinguished. The dark portion of the axis in each figure corresponds to the range of output values where there is uncertainty as to the shape all the object being detected. The dashed line in each figure corresponds to the point at which, depending on the output value, objects can be distinguished in terms of a feature. Figure (4.7) part (d) is the frequency distributions resulting from the fusion of x1 and x2. Without specifying a particular method of fusion, it is usually true that the distribution corresponding to the fusion of redundant information would have less dispersion than its component distribution.

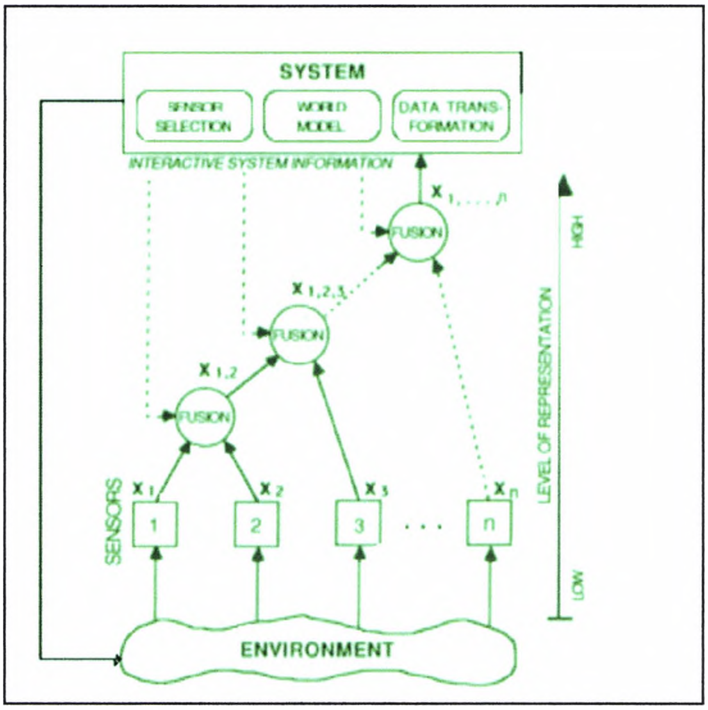


Figure (4.8) General pattern of multisensor integration and fusion in system

sensor failure, and [W. Dress, 1987] has explored the use of frequency-coded sensor information for fusion in neural network.

A neural network is derived from training using extensive input and output data. Depending on the depth and complexity of the network, many thousands of data set may be involved. For this early contribution to the research, it is not realistic to assemble such extensive data.

4.9.1.3 Logical Sensors

Logical Sensors Is a specification for the abstract definition of a sensor that can be used to provide a uniform framework for multi-sensor integration. The use of logical sensors can achieve any multi-sensor system with both portability and the ability to adapt to technological changes in the manner transparent to the system. A representation of the essential elements of the logical sensors method has been worked out. Each logical sensor can serve as an element in a network of logical sensors, which itself can be viewed as a logical sensor. A hypothetical logical sensor based range finder has been demonstrated that incorporates three physical sensors: an ultrasonic range finder and two cameras, for example. In this case, both cameras are used as input to a fast and slow stereo logical sensor. By this means, the entire network of logical and physical sensors can provide for a range finder that is both robust in terms of lighting conditions in which it can operate (i.e. the ultra sonic sensor for poor lighting conditions) and, depending on time constraints, the speed at which it can operate.

Whereas the logical sensor approach can be effective for combined use of different types of sensors all aimed at establishing a single outcome e.g. the distance to a target, it is not clear how it can be extended to the NDT problem. The core issue with the NDT problem is the need to use different types of data from dissimilar sensors. In the target problem, for example, one sensor might be required to detect the colour of the target, an impossible objective.

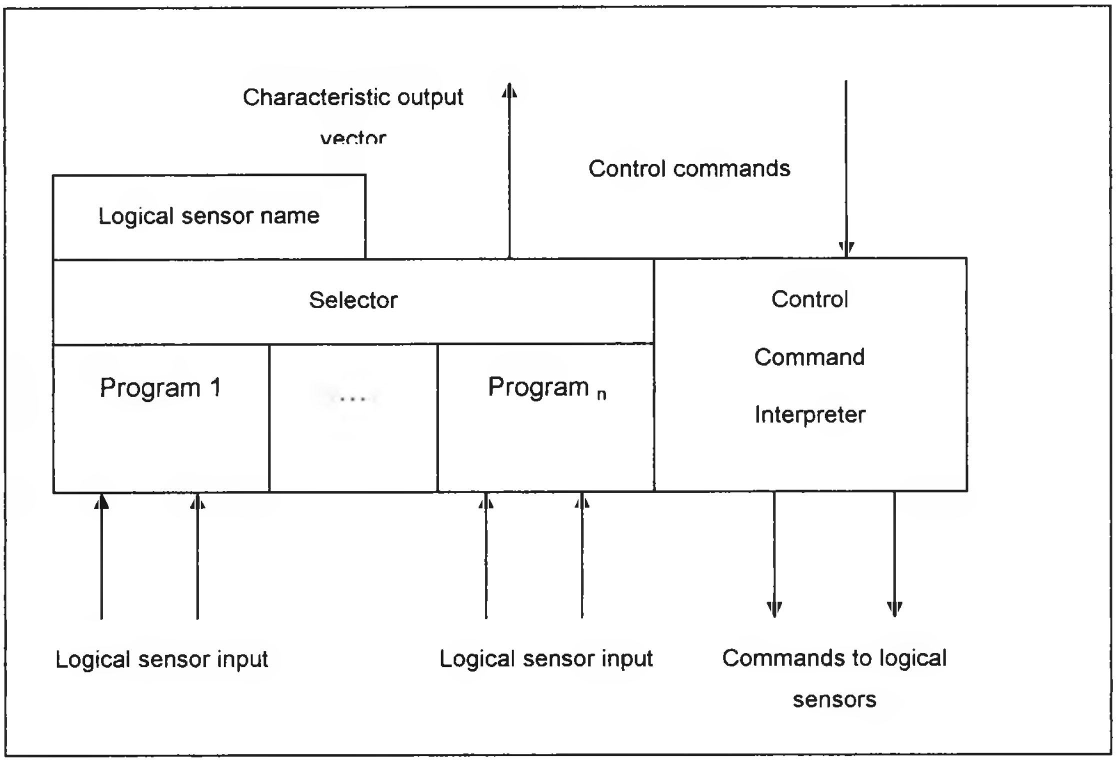


Figure (4.9) Basic Components of Logical Sensor

Figure (4.9) shows the essential elements of a logical sensor. The "characteristics output vector" describes the data type of the stream of output vectors produced by the logical sensor. The "control command" input to a logical sensor consist of both commands necessary to control the logical sensor and commands that are just passing through to other sensors lower in the network. The "control command interpreter" processes the incoming commands and sends appropriate commands to the logical sensor lower in the network. The "selector" monitors the control commands issued to the logical sensor and the result of the various "program unit" – acting as a "micro expert system", which knows the required function of the logical sensor. Each program unit serves to perform any required computation on the input to the unit. The logical sensor inputs are output vectors of logical sensor lower in the network.

When the logical sensors are actual physical sensor, raw data sensed from the environment can be considered as null input. [E. Shilcrat, 1984]

4.9.1.4 Object-Oriented Programming:

In a similar manner to the logical sensors mentioned above, object oriented programming is a methodology that can be used to develop a uniform framework for implementing multi-sensor tasks. In most object oriented multi-sensor applications, each sensor is represented as an object. Objects communicate by passing messages that invoke specialised sensor processing methods based on the sensor's attributes and behaviour. Each method is transparent to the other objects, allowing possibly different physical sensors to be used interchangeably. [E. Weitz, 1988]

This method has clear merits for the NDT problem. Using it should give a good structure for the solution formulation.

4.9.2 Control structures

This section evaluates different structures that have been used to control the overall integration of the fusion process.

4.9.2.1 The NBS sensory and control hierarchy

This method is 'task and goal' driven e.g. a task is set for a robot which can be verified or not (e.g. picked up object successfully). In achieving the goal, the significance and contribution of each sensor can be affected, for example. With the NDT problem there is no opportunity to make use of a closed loop scenarios. In fact, it is necessary for considerable interaction by the human operator, giving weight to the contribution from individual sensors. To achieve this automatically would add a considerable level of complexity, by means of an expert system, for example.

The centre for manufacturing engineering at the National Bureau of Standards (NBS) is implementing an experimental factory called the Automated Manufacturing Research Facility (AMRF). As a part of the AMRF, a multisensor interactive hierarchical robot control system is being developed based on the mathematical formalism called the cerebella model arithmetic computer. [H. McCain, 1985]

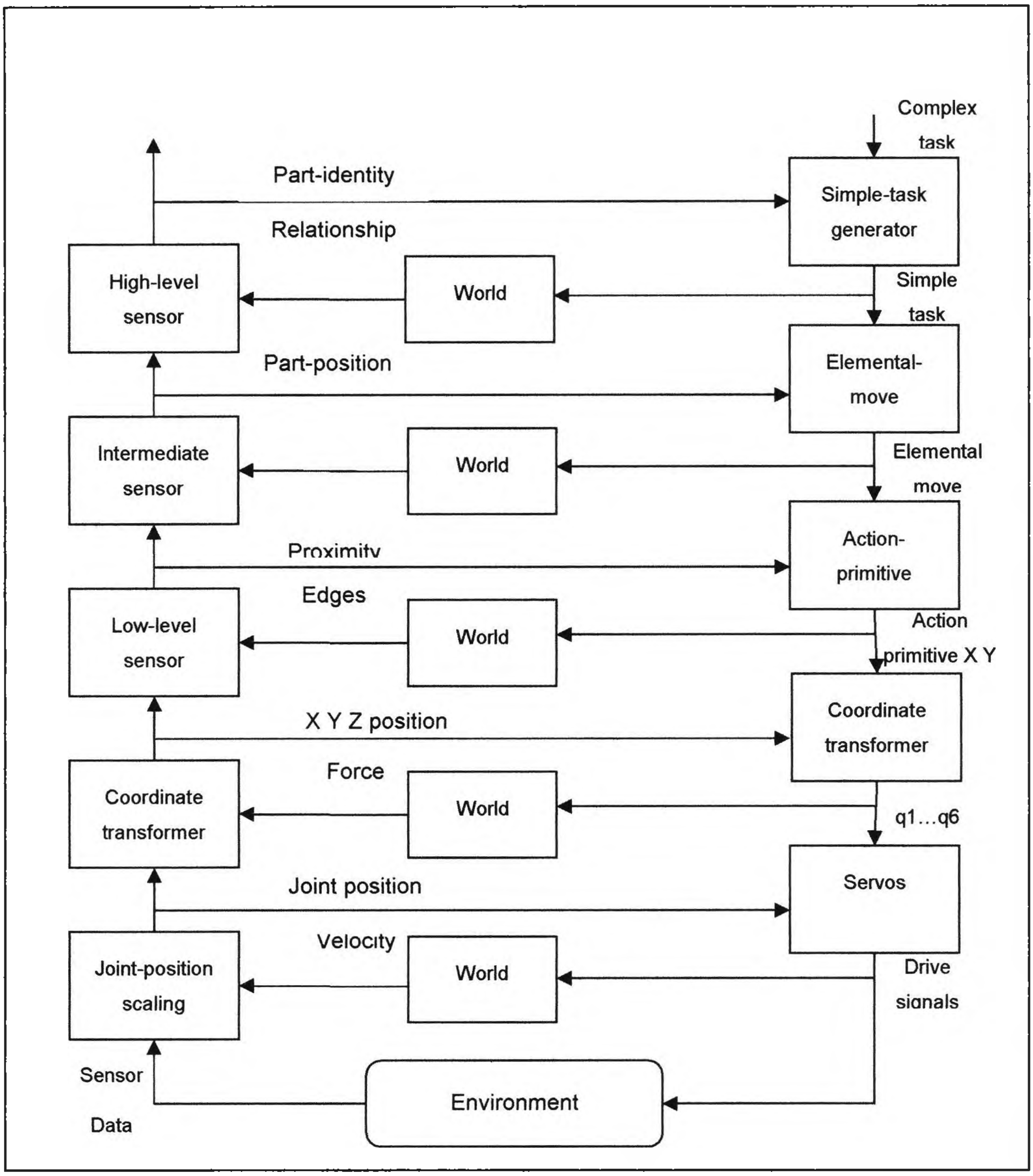


Figure (4.10) NBS Sensory and Control Hierarchy Used to Control Multisensor Robot

The structure of the control system in AMRF, as shown in figure (4.10), consists of an ascending "sensory processing" hierarchy coupled to a descending "task decomposition" control hierarchy via "world models" at each level. The use of multiple levels is motivated by the observation that the complexity of a control program grows exponentially as the number of sensors and their associated processing increases. An example is provided of the control of a multi-sensor robot using the NBS hierarchy. Raw sensory data from the environment enters the system at the bottom. The updated world models can then serve to modify the desired task control action until, at the lowest level, the necessary drive signals are sent to the robot to initiate actions in the environment.

4.9.2.2 Distributed Blackboard

Blackboard architecture allows economical communication between distributed sensory subsystems in an integrated multisensor system. The blackboard can contain any system information needed by the integration functions. Any number of different fusion methods can be implemented using the output from the blackboard.

[S. Harmon, 1986] have used blackboard architecture to compare different methods of multisensor fusion, and he has used blackboard architecture for autonomous vehicle control. The idea of Blackboard is very interesting but there is a lack of hardcore and transparent implementations in the literature. It is a top level concept for combining different solution possibilities within a fixed structure. For NDT problem in hand, this not considered helpful.

4.9.2.3 Adaptive Learning:

Adaptive learning is a control method in which the system "discovers" the appropriate signals for control based on the output of its sensors. The system is taught a representative sample of correlated control signals and associated sensory outputs over the range of signals and sensory outputs encountered by the system. Based on the associations developed during the teaching phase, it is possible to have the system respond to any combination of sensory outputs with a suitable control signal. This particular feature of the adoptive learning approach can be attractive for the user involved in otherwise complex output. [W. Miller, 1986]

The idea of adaptive learning is useful for the NDT problem. For example, in wet conditions the contribution from the half cell observations would be reduced in significance. In implementation, however, it is unlikely that full automation would be possible until a substantial bank of case study data could be assembled in the future.

4.9.3 Sensor selection strategies

Two different approaches to the selection of the type, number and configuration of sensors to be used in the system can be distinguished; pre-selection during design or initialisation and real-time selection in response to changing environmental or system conditions [S. A. Hutchinson, 1986].

4.9.3.1 Pre-selection

A general relationship between the number and operating speed of available sensing elements as a function of their response and processing times has been derived. This relationship can be used to determine the optimal arrangement of the sensing elements in a multi-sensor system. [G. Beni, 1983]

4.9.3.2 Real-time selections

[F. Hutchinson, 2001] have presented an approach to planning sensing strategies for object recognition in a robotic work cell. One sensor is used to form an initial set of object hypothesis and then subsequent sensors are chosen so as to disambiguate maximally the remaining object hypothesis.

4.9.4 General fusion methods

Most methods of multi-sensor fusion make explicit assumptions concerning the nature of the sensory information. The most common assumptions include the use of a measurement model for each sensor that includes a statistically independent additive Gaussian error or noise term, and an assumption of statistical independence between the error terms of each sensor.

A summary for comparison the relevant aspects of each general multisensor fusion method have been presented [J. Richardson, 1988]. The sequence in which the methods are presented corresponds roughly to the increasingly high levels of representation of the information being fused. Included in the given table (4.1) are the means used to represent uncertainty in the measurement and fusion processes, possible methods used to determine the consistency of sensor measurements, and the actual techniques used for fusion. [L. Pau, 1982]

METHOD	Operating environment	Type of sensory information	Information representation	Uncertainty	Measurement consistency	Fusion technique
Weighted Average	dynamic	redundant	Raw sensor readings		Thresh holding possible	Weighted Average
Kalman Filter	dynamic	redundant	Probability distribution	Additive Gaussian noise	Thresh holding, calibration	Filtering of system model
Bayesian Estimation using Consensus Sensors	static	redundant	Probability distribution	Additive Gaussian noise	Largest digraph in relation matrix	Maximum Bayesian estimate of consensus sensor
Multi-Bayesian	static	redundant	Probability distribution	Additive Gaussian noise		Maximum Bayesian estimate
Statistical Decision Theory	static	redundant	Probability distribution	Additive Gaussian		Robust minimax decision rule
Evidential Reasoning	static	Redundant and complement	proposition	Level of support versus		Logical interface
Fuzzy Logic	static	redundant and complementary	proposition	Degree of truth		Logical interface
Production rules	static	redundant and complement	proposition	Confidence factor		Logical interface

Table (4.1) General Methods of Multisensor Fusion

4.9.4.1 Weighted Average

One of the simplest and most intuitive general methods of fusion is to take a weighed average of redundant information provided by a group of sensors and use this as the fused value. While this method allows for the real-time processing of dynamic low-level data, in most cases the Kalman filter is preferred. This is because it provides a method that is nearly equal in processing requirements and, in contrast to a weighted average, results in estimates for the fused data that are optimal in a statistical sense.

This approach is relevant to our NDT problem, where weighting of each sensor contribution is necessary in the fusion process.

4.9.4.2 Kalman Filter

The Kalman filter uses the statistical characteristics of the measurement model to estimate recursively for the fused data that are optimal in a statistical sense. If the system can be described with a linear model, and both the system and the sensor error can be modelled as white Gaussian noise, the Kalman filter will provide unique statistically optimal estimates for the fused data. The recursive nature of the filter makes it appropriate for use in systems without large data storage capabilities. [P. Maybeck, 1982]

On the basis of the above, use of the Kalman Filter method is very relevant to the NDT problem.

4.9.4.3 Bayesian Estimation using Consensus Sensors

The central idea behind this method is first to eliminate from consideration the sensor information that is likely to be in error, and then to use the information from the remaining "consensus sensors" to calculate a fused value. A functional block diagram of the method will be presented in figure (4.11). The information from each sensor is represented as a probability density function. Given readings from "n" sensors in the system, the resulting information is first made commensurate through re-processing. An "n" by "n" distance matrix is created by calculating for each element (i,j) in the matrix the "confidence distance measures" between the information from sensors "i" and "j". A confidence distance measure is twice the area under the density function of sensor “i” between the readings from sensor “i” and sensor “j”. The optimal fusion of the information is determined by finding the Bayesian estimator that maximizes the likelihood function of the consensus sector. [M. Lin, 1987]

This method is very appropriate to the NDT problem because it combines statistical processing within a decision hierarchy. It also is particularly appropriate when different sensors are used together.

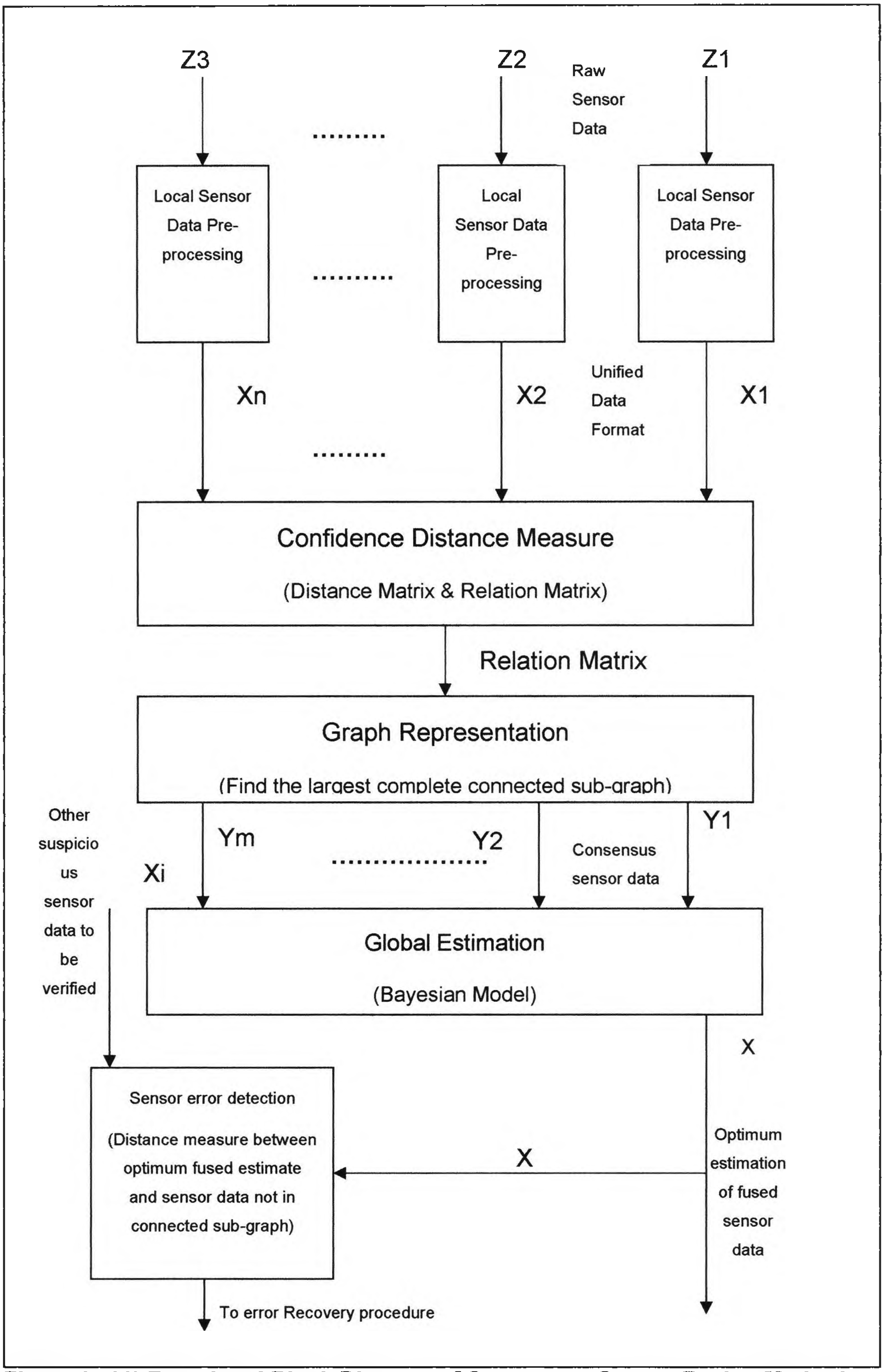


Figure (4.11) Functional Block Diagram of Consensus Sensor Fusion Method

4.9.4.4 Multi-Bayesian

Each sector in the system is described by its ability to extract useful static descriptions of these objects. An "e-contaminated" Gaussian distribution is used to represent the geometric objects. The sensors in the system are considered as a team of decision-makers. Together the sensors must determine a team-consensus view of the environment. [H. F. Durrant-Whyte, 1988]

This is a useful extension to the Baysian approach, which fits closely with the NDT problem.

4.9.4.5 Statistical Decision Theory

Sensor noise has been modelled as the "e-contamination" of a variety of possible probability distributions. The use of "e-contamination" in the sensor model serves to increase the robustness of the decision procedure. That's by removing a certain outlying fraction "E" of the distribution to account for deviations from the assumed noise distribution that may have been caused by spurious sensor readings. Initially, the data from different sensors are subject to a robust hypothesis test as to its consistency. Data that passes this preliminary test are then fused using a class of robust decision rules. [M. Mintz, 1988]

Exclusion of sensor noise is an important aspect of the NDT problem. This serves to strengthen the quality of the contribution from each sensor in the decision outcome process.

4.9.4.6 Shafer-Dempster Evidential Reasoning

Shafer-Dempster evidential reasoning is an extension to the Bayesian approach that makes explicit any lack of information concerning a proposition's probability by separating firm support for the proposition from just its plausibility.

In the Bayesian approach, all propositions for which there is no information are assigned an equal a-priori probability. When additional information from a sensor becomes available and the number of unknown propositions is large relative to the number of known propositions, an intuitively unsatisfying result of the Bayesian approach is that the probabilities of known prepositions become unstable. In the Shafer-Dempster approach this is avoided by not assigning unknown propositions an a priori probability (unknown propositions are assigned instead to "ignorance"). Ignorance is reduced (i.e. probabilities are assigned to these propositions) only when supporting information becomes available. [G. Shafer, 1976]

In the NDT problem it is important to be able to handle gaps in sensor data without negatively affecting the quality of the outcome. For this reason this refinement is adopted with the Baysian method.

4.9.4.7 Fuzzy Logic

Fuzzy Logic is a type of multiple-valued logic, which allows the uncertainty in multi-sensor fusion to be directly represented in the inference (i.e. fusion) process by allowing each proposition, as well as the actual implication operator, to be assigned a real number from 0.0 to 1.0 to indicate its degree of truth. [L. Zadeh, 1965]

Fuzzy logic gives a way of handling the interface between qualitative and quantitative data. It also gives a way of combining different types of data by transferring them into a common numerical basis.

4.9.4.8 Production rules with a confidence factor

Production rules are used to represent symbolically the relation between an object feature and the corresponding sensory information. A confidence factor is associated with each rule to indicate its degree of uncertainty. Fusion takes place when two or more rules, referring to the same object, are combined during logical inference to form one rule. The major problem in using production rule based methods for fusion is that the confidence factor of each rule is defined in relation to the confidence factors of the other rules in the system. This makes it difficult to alter the system when, for example, new sensors are added that requires additional rules. [S. Kamat, 1985]

With the NDT problem, a general rules for a fixed number a type of sensors cannot the set. The importance of each sensor will vary according to the testing environment, type of structure and the dominating condition/defects. In the NDT problem it will be more effective if the production rules remain in the hands of the human operator. With extensive case study experience beyond the research, however, automated production rule are probably feasible.

4.10 Conclusions

In this chapter different theories and approaches to the NDT problem have been reviewed and observations on their relevance made. Reasons for discarding or using them in the solution formulations are given.

The majority of the data fusion methods reviews in the above are only feasible for multi-sensor systems comprising identical or very similar sensors. In aircraft safety system, for example, 3-4 identical sensors are used to measure the same critical quality. Here, the role of data fusion is typically to add confidence to go/no-go states. For this reason, the author has decided to investigate an approach which is broadly a combination of the statistical and weighted methods. This approach has been encoded as a Stage 1 model implemented using Visual Basic and Excel. In the Stage 2 model, subsequently investigated, Bayesian logic combined with a rule based Expert System is being added to the Stage 1 model.

Chapter 5

DATA FUSION PROCESSING: STAGE 1

5 Data Fusion Processing: Stage 1

5.1 Introduction

This chapter describes the computer programme that has been encoded to test the effectiveness of a general data fusion method based on statistical processing of raw data combined with user-applied weighting. This program allows data to be collected by the different sensors at non- concurrent positions. The restrictions on the surveyor would otherwise be unreasonable. The rebound hammer is typically applied within a 40mm diameter for a single point statistical value, for example. This reflects the fact that it can cause local damage at each impact point. On the other hand, multiple half-cell values can be taken at a single point for that point's value statistics. There is also a difference in the density of survey sampling with the different sensors.

The computer program calculates the statistics for each collection point and recalculates these for required interpolation points. Use of interpolation allows data to be combined for a single point. Steel reinforcement diameter, position, cover and corrosion occurrence is separate from concrete condition i.e. shallow strength by 'Schmidt Hammer' detection. In the second stage of the program, the user is able to investigate the effect of weighting values on a combined data result. It is interesting to combine the effects of low reinforcement cover with co-occurrence of low resistively (active corrosion activity). Interpolation is achieved by fitting a spline function to the statistically processed sensor data.

5.2 Computer Software

The software is derived from a combination of Visual Basic and an Excel Spread Sheet. Input data is set up in an Excel Table and thus the main purpose is to calculate a mixture of these data results. For correct calculation, several conditions are considered for input (Excel) data.

5.2.1 Conditions for input data

The Excel sheets are labelled as it is shown in figure (5.1) below. Realistic source data is simulated for rebound hammer, covermeter (size and cover), half cell potential and resistivity. The data from each probe is processed statistically for statistical mean and Standard Deviation.

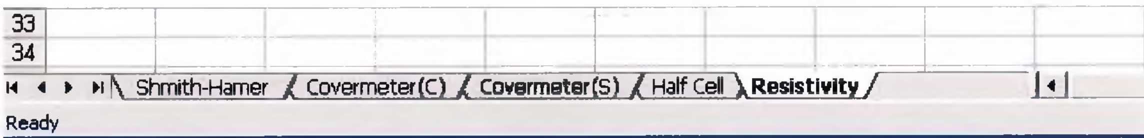
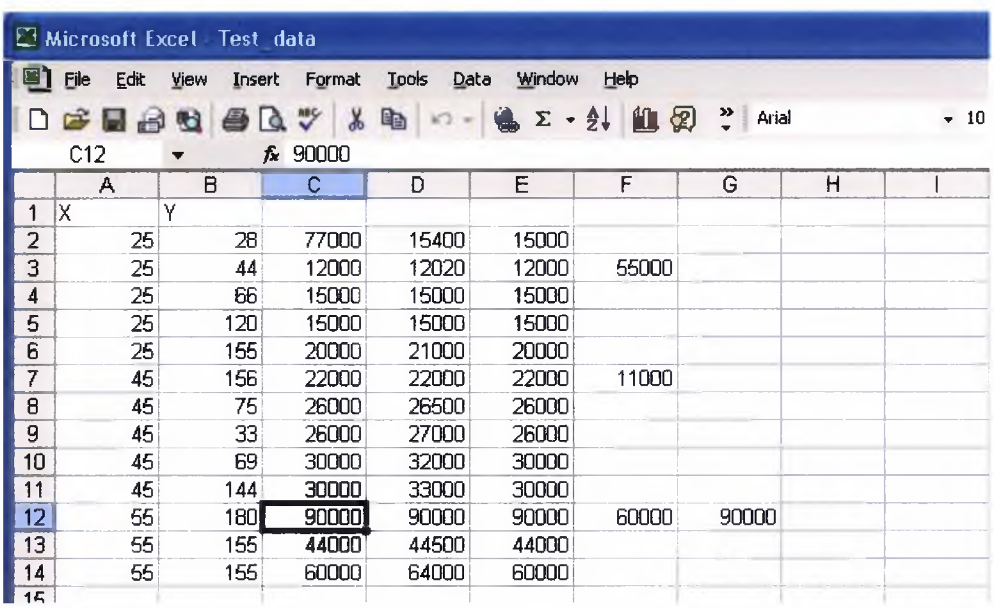


Figure (5.1) View of Excel Table

The data format is represented in the following figure, x and y representing a data point position.



	A	B	C	D	E	F	G	H	I
1	X	Y							
2	25	28	77000	15400	15000				
3	25	44	12000	12020	12000	55000			
4	25	66	15000	15000	15000				
5	25	120	15000	15000	15000				
6	25	155	20000	21000	20000				
7	45	156	22000	22000	22000	11000			
8	45	75	26000	26500	26000				
9	45	33	26000	27000	26000				
10	45	69	30000	32000	30000				
11	45	144	30000	33000	30000				
12	55	180	90000	90000	90000	60000	90000		
13	55	155	44000	44500	44000				
14	55	155	60000	64000	60000				

Figure (5.2) Data Presentation in Excel File

The first point should be situated on row 2 as X, Y, and data columns with a minimum of 5 data values. This is required for each point to enable calculation of the individual point statistics. The Excel table is saved as an Excel file on disk. Following this, the actual Visual Basic program presents two panels, the General Panel and Calculation Panel. The former stage relates to statistical processing of the raw data and the latter stage the application of the weighting method. These are shown in figures (5.2), (5.3).

5.3 Statistical Processing

The General Panel appears first when the program is started. Typical content is shown below in figure (5.3).

5.3.1 User Step1

The user has to download the collected data from the Excel table. For this purpose the button "Load Excel data" is designed. By clicking this option, the user will be able to select Excel file form the computer. The computer will open "windows explorer view" expecting file to be selected from the machine. Special designed parser will check for selected file extension and if the file is not Excel format the system will show a warning message on the screen. If an appropriate file is selected, the system will transfer the data into RAM memory and all measurements from this file will be shown on the General Panel in the bottom left of the screen. A special parser transforms each data in an appropriate easy to edit format. If the user wishes to view the excel datasheet as it was originally presented, "Show Excel table" box must be selected. This way the system opens a second screen which will be the original excel table with the data. This important step loads data into the program memory allowing further calculation and data analysis. Performing calculations on the original excel table is not advised. During the calculation process the program uses copy of this original data. (Excel file is left intact from the system for safety reason)

The reason for transferring the data format from excel to something more complicated is to allow the user to have better view on the data in terms of analytical and statistical presentation. The new format is presented in a special box which allows editing of the data. The format consists of the following fields:

- number of measured point
- device performed the measurement
- X coordinate
- Y coordinate
- Number of repeated measurements for this point

- Max value
- Min value
- Mid value (see equation 1)
- Standard deviation (see equation 3)
- And all data from this measurement

This field is editable and any changes on it effect the global recalculation of every further step. This field can be used to ignore or correct obvious mistakenly obtained data. For example, if the standard deviation of all data is around 1.1, and it is known from experience that in the worse case is SD<3, then a value giving SD=5.0 would result in that data being ignored. Then, manually, the user would find this measurement and delete it from the memory by the editable data box in the program (bottom left corner). By doing this the system will recalculate the data and show the new statistical representation of the measurements.

This important step is provided to ignore external noise and help the system to reduce the number of calculations. At the same time the user should be experienced and more responsible to what changes have been made to the initial data.

5.3.2 User Step 2: Producing satisfactory input

By looking at the statistical data (min, max, mean, SD), the user must locate and ignore noises into the data.

Looking at the middle box, which represents statistical data for every channel, it is possible to locate a noisy, misplaced or wrong measurement. Checking the exact location of data detected by a given device is achieved in the early stage of the programme. It is possible to locate even a single wrong measurement and after editing it (change or delete) the system recalculate all data. New statistical values will be displayed for the channels as the result of this action. Checking these outcomes and values, and performing changes on the data until satisfactory performance is finally calculated, is recommended. This process may require several changes on different data. The system is not clever enough to perform this initial noise filtering. This step requires experienced users. The reason for wrongly obtained data can be either, special conditions in which the data has been obtained, or a not well calibrated device or technical problem.

5.3.3 User Step 3: Monitoring different points for each channel

The final goal of the system is to produce smooth surface rather then points. Having surface information makes the final conclusion precise. Also, it makes it much easier to conclude the reason for having these data at a particular location. To obtain a surface is not an easy task. The user has to monitor different locations, to choose the algorithm and optimum view of the surface.

The middle white field represents the surface and the red boundary is automatically generated from the data representing the point with greatest coordinate values (X, and Y). The maximum values of the X and Y are shown also at the end of the X and Y axes. All measured points are located in the top left corner of the field, and the small dots represent every measured point. The coordinates represents real measured values with the system performing dynamic conversion of the values from real to virtual values (pixels on the screen). For the user, all data is real data, making the graphical operation more "user friendly".

All represented points are dynamically updated if changes in the initial data are made. The user can obtain information for virtual measurement for every point in the surface by clicking on the particular location or placing coordinates of X and Y in the fields X and Y, located at the top of the graph and then pressing the button "go".

The system calculates the point value using the mathematical approximation model chosen form the selection located at the bottom of the graphical Slab representation. The initial action of the user in this step is choosing the device for which the graphical representation will be performed. This can be done by selecting the radio button in front of the chosen channel. Initially the system selects the first channel, but the user can change this at any time. Selection buttons are located at the top left corner of the screen in front of each channel.

For every point, calculations and a short activity description appear in left bottom corner of the screen in a special field. This is an editable field in which the user can store all performed measurement and, at the end, add this information to the final report.

After selecting the channel, the user can select the mathematical algorithm for data approximation. Data approximation in this system is performed using the values of several nearest points. The exact algorithm can be selected by clicking the box in front of “3” at the bottom of the graphical field. In the example this means that the user choose “3 closest points” whereas the system initially uses 2 nearest points. Calculation of the Bayesian distance to the nearest points is mathematically related to the required value. The mathematical calculation of this approximation method is described in equations 9-13 in chapter 6. “Points data” field adds the new values of the calculated points in the bottom of the field, preserving all previous calculations. The meaning of this calculation is to satisfy the user with approximated algorithm and, at the same time, allow testing of special or critical points and zones from the surface. Recording of specially calculated points on the graphical screen is preserved in a special format.: (i) device from which the point originates, (ii) data for each closest point (iii) distance, (iv) method of approximation used and (v) value for the approximated point. The important issue is that the system represents (based on probability calculation) every value obtained from the initial data in 5 zones. These zones are obtained by calculation of the SD field for every point, the system determining SD's in 5 subfields. The value represented to the user is how many data points (%) for a particular point are these 5 fields situated in. This is important because it gives a full description and information for data representation, especially when the user works with special or critical points on the surface. This graphical field also can calculate and represent graphically every point for particular channel (this function will not input data in “point's data” field). Additionally, it can be seen that all points for all channels are included in one graph, which allows the user to see all measured locations and areas where measurements are missing. The button “Clean Picture” cleans the graph and makes the system undertake fresh calculations for the selected channel.

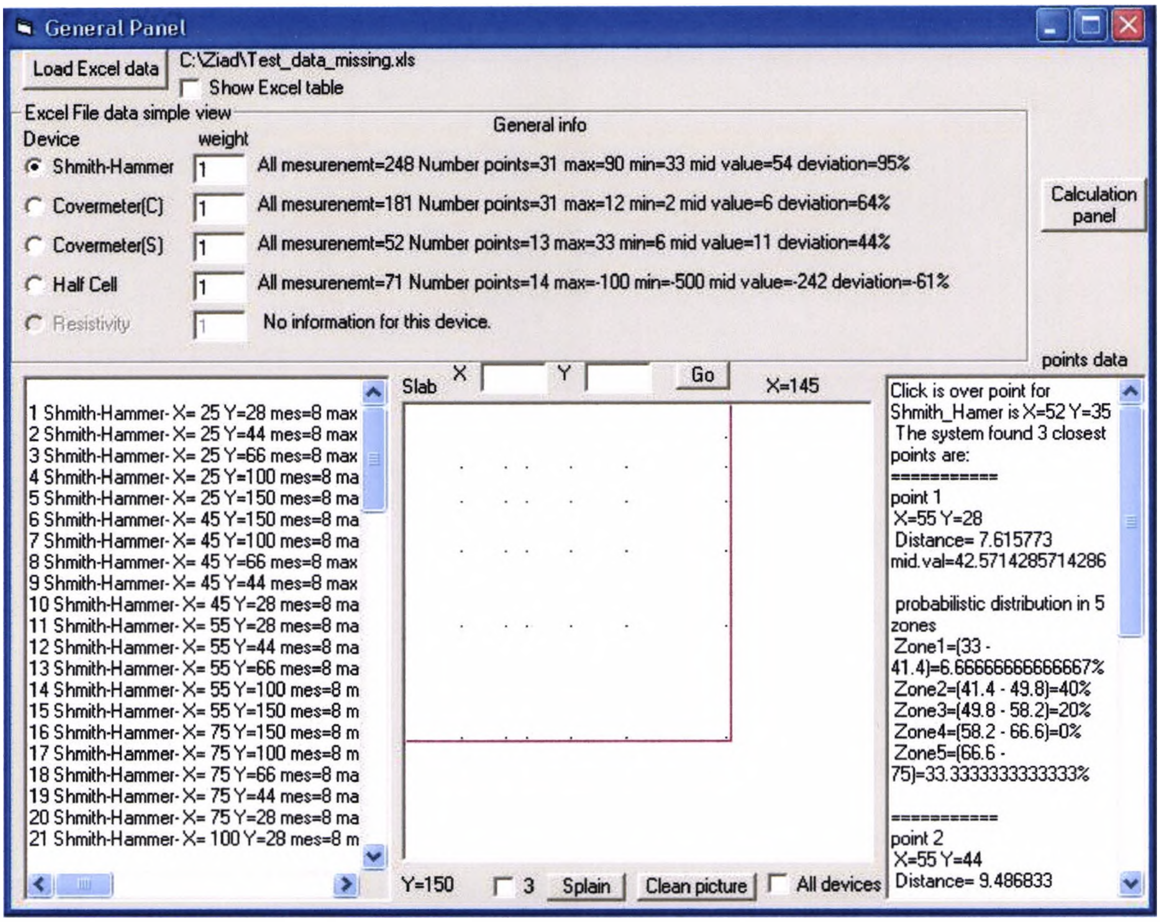


Figure (5.3) General Panel of the System

As can be seen in figure (5.3), this panel shows the statistics worked out for a particular sensor (Schmidt Hammer example shown), including the number of data points, maximum, minimum, middle and SD. The matrix of data points is set out in the lower middle window. Whilst the SD value appears large, the final outcome will typically be substantially more reliable due to the data fusion process.

The General Panel consist of several fields and buttons, the most important being the 'LOAD EXCEL DATA' button. This button causes loading of real Excel data from a file to the computer memory and opens the typical menu. Near to the 'load excels data' button the file path and the name of the Excel file can be seen. The panel 'Excel file data simple view' shows the available NDT devices. In this case, the Resistivity data are not available. The first available device is shown ticked as an actual active device in the system, the Schmidt hammer in our case.

To analyse in a convenient way, the user can approximate every known point on the slab and fit a spline to the positional data (surface structure presenting the unknown points using the known). This can be viewed by pressing the 'Spline' button. Unfortunately, the calculation is very slow because of the complexity. Also, the spline function can be calculated using the nearest 2 or 3 points on the slab. The system uses 2 points, but if one wishes to start this calculation for 3 points, the box named 3 (bottom of the screen) is ticked. Instead of clicking over the slab with the mouse, one can use the X and Y boxes and press the 'Go' button. This produces the same information as clicking over points with the same X and Y position. Sometimes, it is useful to check all points for all devices in the slab. In this case, it is necessary to click in the 'All devices' checkbox. In this situation, the user not allowed to make a spline fit.

The button 'clean' can be used to delete previous information written over the graphic. This button can be used if the user wishes to compare different sensor values over the same area (clicking over the first device produces the graph). Data for both can be compared by overlaying sensor results.

5.3.4 User Step 4: Weight and weighting factor

Weight is a special variable which has been included in calculation. This coefficient cannot change data statistically, but it can change the involvement of particular channel in the final mix. The weight is important because it can improve the result by involving the user opinion to influence the result and at the same time minimises the required computational power. For example, if Resistivity is included as one of the NDT methods used in investigating a structure and the construction has been exposed to a heavy rain or flooding. In this case the data are not very representative. The standard deviation of this channel is the greatest and several data items have been removed to stabilise the statistical results. These factors can mean that this channel is not as representative as the other NDT methods used to investigate the same structure. The system can include complicated mathematical algorithms but it would not be clear to the user that this NDT method should not be used or, in another words, this particular method should not have a big influence on the overall condition of the structure. The other reason can be an application problem, for example, if the surface is not even everywhere measurements obtain with Schmidt-Hammer are not accurate.

The weight factor includes a subjective component that is difficult or cannot be produced mathematically. No matter what will be the weighting factor in the field in front of the channel, the system will normalize the result in further calculations, taking in account the weight for every used channel. Further calculation for data fusion (presented in the second screen figure (5.4) will include only information for the surface as good or bad and thus any specific information why will be lost. For investigating specific problems, the only option is to go back and analyse the information on the first screen.

5.3.5 User Step 5: Performing data fusion.

After satisfactory performance of the data in the first screen, the user is ready to mix the processed data in data fusion calculation. Pressing the 'Calculation Panel' button produces the panel shown below in figure (5.4). From this panel it is possible to return to the 'General Panel' to check the survey data and its statistics.

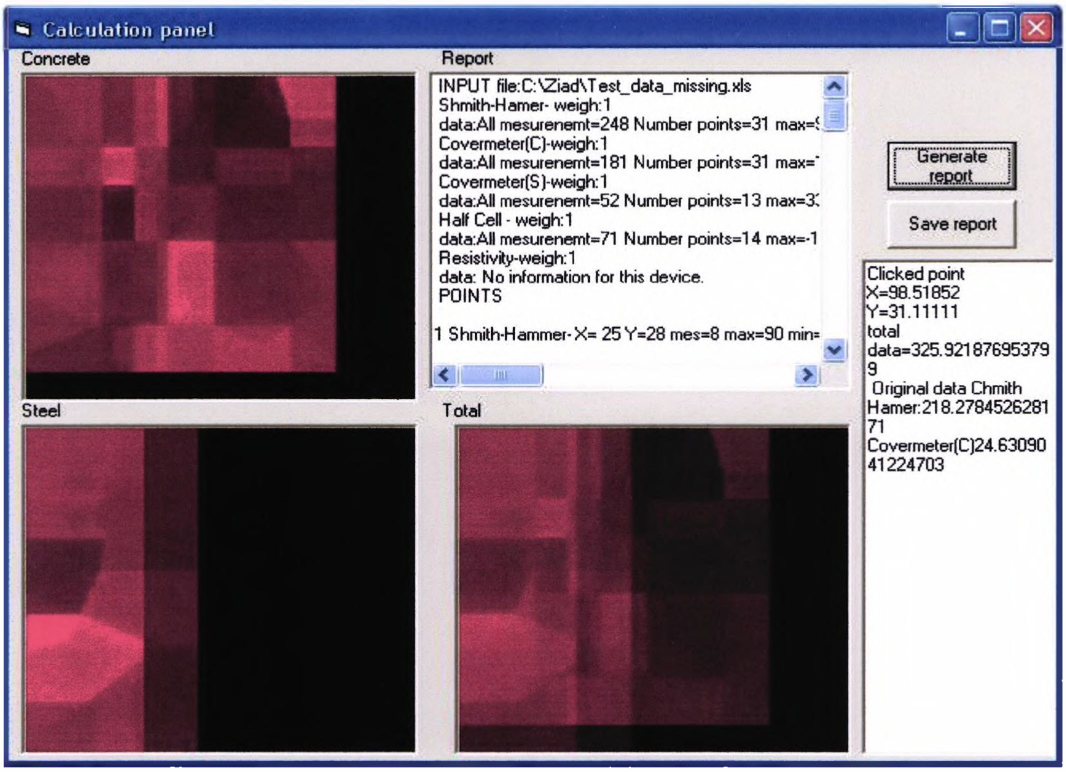


Figure (5.4) Calculation Panel

The 'Calculation Panel' presents the normalized data and the weighted combinations of them for the whole slab. Detected reinforcement 'steel' is shown separate from 'concrete' condition parameter values. The report text field is usually empty and can be filled with initial information if the user presses the button 'Generate report'. Results for a chosen position on the graphics (selected using mouse cursor) are automatically displayed as text in the right-hand panel. If the outcome is suspect, the user can return to the initial 'General screen', checking more carefully the raw and statistically processed data.

Finally, the user can write the reports to the disk, this initiated using the 'Save report' button. This operation saves not only the report as a text but also the three screen displays from the Calculation panel (Steel Reinforcement, Concrete and Total). Premature closing of any part of the screen display must be avoided because this can destroy the calculation process of the program.

The user can analyse any point shown on the left two screens representing Steel and Concrete data. The mathematical explanation of how the point is obtained can be seen on the special field in the left side of the screen. If the user cannot conclude why the data is with some particular value (or colour) and needs further analyses, they can return to the previous screen where the statistical representation of all data is available. Judgment of the quality of the surface can be precisely done by monitoring the representation of different patterns in the last screen. Unfortunately, this screen cannot give any information about reasons of a particular points if the condition shown as good or bad, as during the mixing process specific information is discarded.. However, this can be done by multidimensional mixing, the author's target at this stage.

Using a Pentium II computer, the calculation to produce the 'Calculation screen' from 'General screen' can takes more than two minutes.

5.3.6 User Step 6: Report

This is the final stage of the program execution, where the special field called "Report" is designed to accommodate all information to be included in the final report. All points tested during the analyses can be pasted in the report. It is fully editable and gives full freedom to include or exclude information in the report. All pictures during the analyses can be also saved to disk..

The user finishes the fusion procedure by pressing "Generate report" button for automatic report creation (all data and analyses will be inserted automatically in Report field). After editing, the user can save all work to a local disk by pressing "Save" button.

5.4 Experiments with fusion tool

An example using real NDT inspection results will be illustrated in order to give a clear picture of the way this programme functions..

The data was collected using four different NDT methods; Schmidt-Hammer, Covermeter, Half Cell and Resistivity. These NDT methods have five sets of data because, in the case of Covermeter, there are both reinforcement diameter and the concrete cover values. All data was inputted as an Excel file. The following is a complete illustration of all steps and a shot of each screen are given:

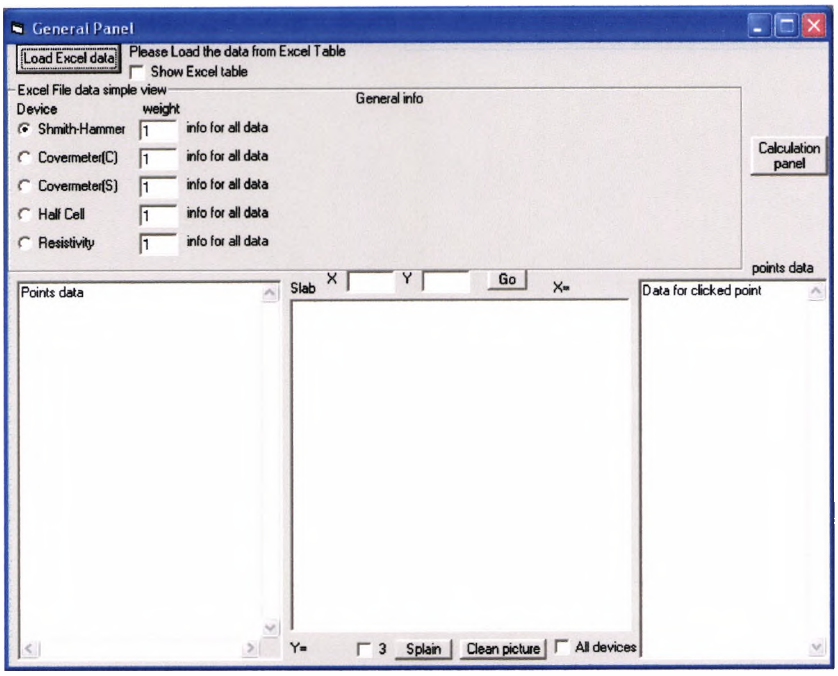


Figure (5.5) Screen 1

By clicking on the "Load Excel Data" the user then locates the Excel file that has all the NDT collected data as figure (5.6)

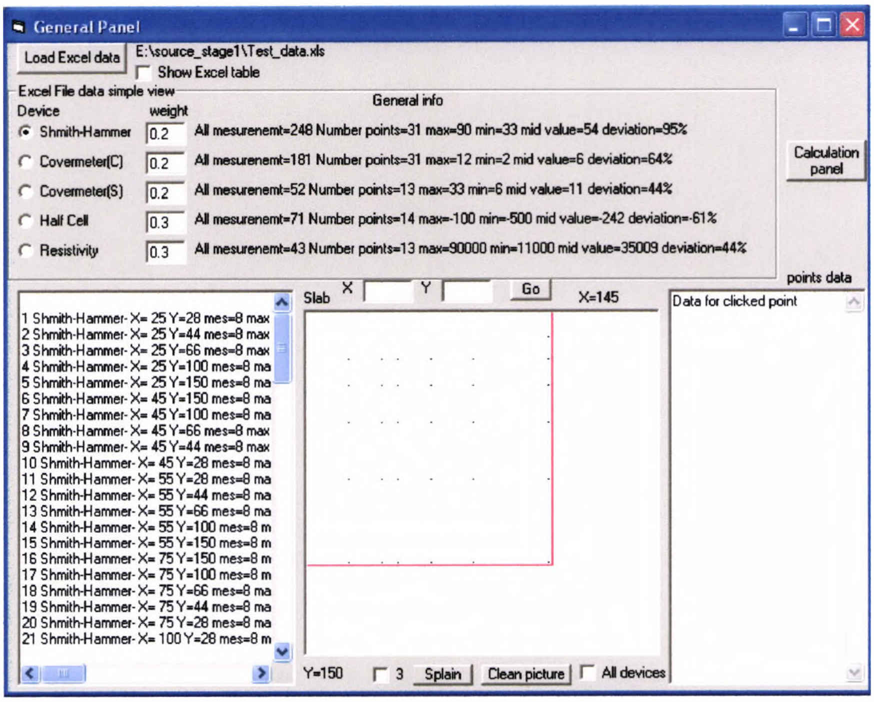


Figure (5.6) Screen 2

At this stage, the user has the option of changing the weight for each sensor or each NDT method. This screen displays all the data including statistics and general information.

The following screen shows the output the user gets by clicking anywhere in the rectangle slab under investigation. As illustrated in figure (5.7), there is a full set of data and exact coordinates for each NDT method.

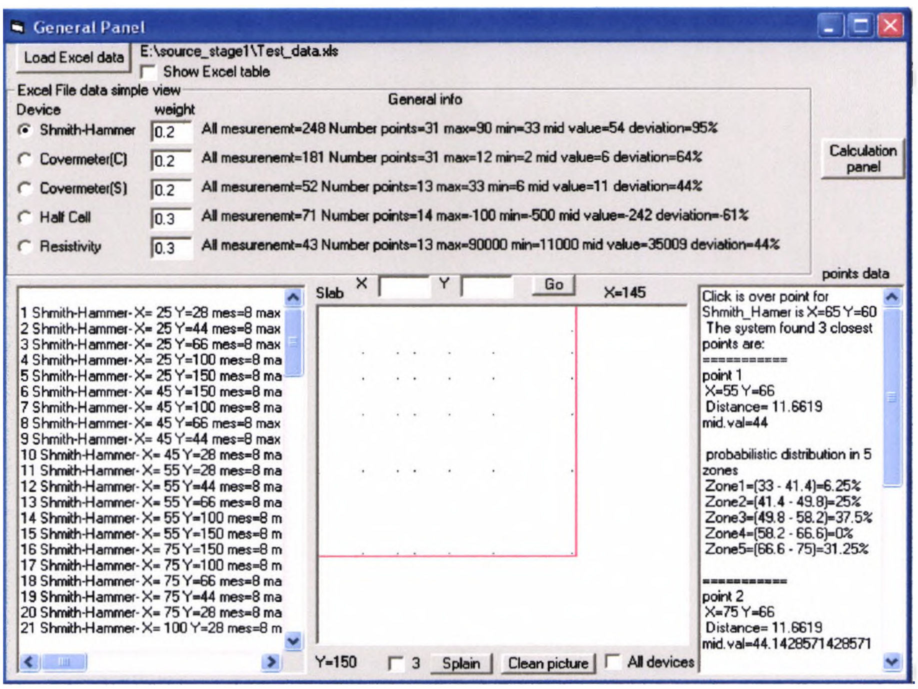


Figure (5.7) Screen 3

And by clicking on the "Calculation Panel" a new screen appears to show the view fusion output of the programme graphically. At this stage four small screens show the steel condition, the concrete condition and fusion of both. The last screen gives details of the chosen location in the slab. Figure (5.8) below illustrates this stage.

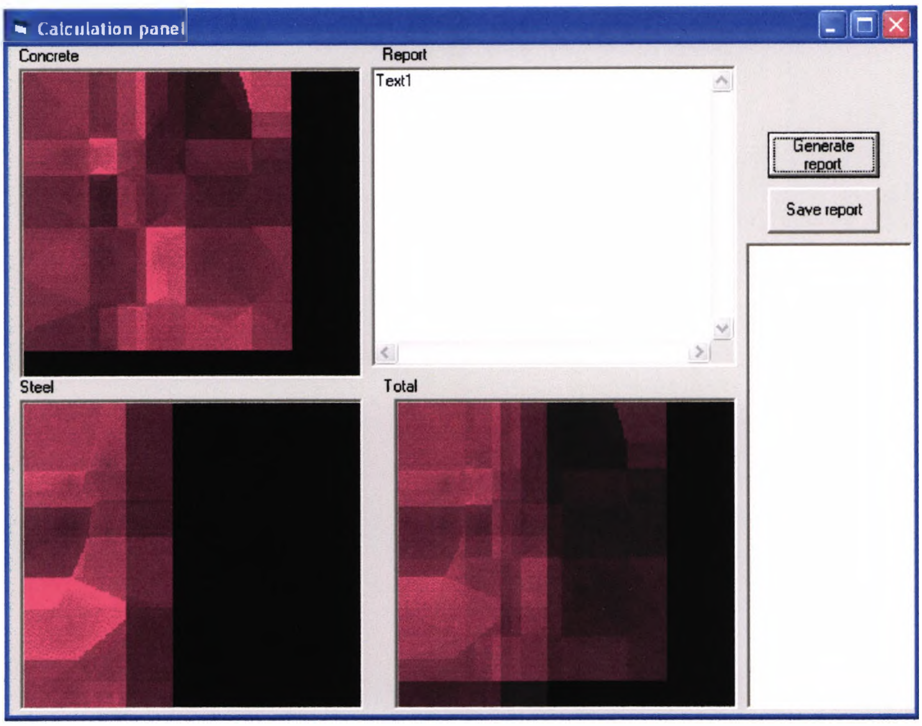


Figure (5.8) Final Screen

5.5 Conclusions

The program works well and is useful for investigations into weighted combinations, giving different views on the concrete condition problem. Ideally, the data should be processed into a single condition parameter number. The basis for this remains to be investigated. However, it is clear that causal knowledge needs to be incorporated into the process. Rather than have absolute outcomes, there also needs to a statistical backbone based on certainty. Running the Stage 1 model within such a framework is covered in Chapter 6. The form of a typical rule for this is as follows:

Rule N

If V1:C1 is less than V2:C2

And V3:C3 is equal to V4

And V5:C5 is not less than V6

Then V7 is equal to V8 : K1

In this rule, each of the compared values of objects VI to V6 has themselves a certainty 'C' value derived from statistical processing of their data set. Rather than the conclusion V7 = V8 having a simple binary value (YES is equal or NO not equal), the outcome of YES (and NO) will have attached certainty values (K1 and 1-K1). It should be noted that the syntax used in the above rule is symbolic rather than actual computer code.

Investigation of the use of causal knowledge on the above lines represents the remaining work for the research. The actual rules will take the typical form:

Rule: Corrosion Probable

If Resitivity_Value:C1 < RV1

And Cover_Value:C2 < 15

Then Corrosion Probable is Corrosion Highly Probable:

K2

Chapter 6

DATA FUSION PROCESSING: STAGE 2

6 DATA FUSION PROCESSING: STAGE 2

6.1 Introduction

This chapter builds on the previous chapter in which the so call Stage 1 approach to data fusion was presented. Whereas the previous model is simplistic, using a weighting system, the Stage 2 model employs sophisticated mathematical and statistical algorithms. This builds on the review presented in chapter 4, which presents state of the art approaches to data fusion. The method represents a significant advancement on the Stage 1 approach. As with Stage 1, experiments are run and evaluated using various NDT data from concrete repair investigations.

The chapter introduces several key problems in Data Fusion analyses and Signal Processing techniques [D. William, 2001]. However, it demonstrates that the presented method has many advantages over the Stage 1 approach and traditional decision making. Time saving and accuracy in decision activity are important advances.

Finally, based on real case studies and expert knowledge, a prototype system is developed and tested. This software performs Data Fusion on several signals obtained from concrete condition detectors. The final judgement is created by multiple iterations between the user and the machine (optimisation process). This performs optimum fitting of the model in terms of time and accuracy. [T. Telford, 2002]

At the end of this chapter, conclusions and different possibilities for model extensions are discussed. Source code, graphs and tables are also provided at the end of the chapter.

6.2 Objectives

The main objective of this chapter is to improve the industrial approach to non-destructive methods in concrete analysis. This leads to several challenges as time-accuracy scale, signals validity estimation, signal fusion and industrial costs in the final implementation. This chapter addresses a more advance system for data fusion based on a combination of rule based approach, statistical calculation, visual data analyses, reverse algorithms for data filtering, and automatic data collection for final report. The main objective is to transfer some of the decision making process from the user to the machine (program) by better interaction between the machine and the human, and by using expert knowledge stored in database as advice to the user. Such a system will rely less on the user experience, which makes it more user friendly

6.3 Rationale

Data fusion is an approach to processing data that has had some notable successes, primarily in the defence sector. However, it is thought that the use of excess data to increase reliability of results, or careful employment of complementary data indirectly to achieve previously inaccessible results, will be of benefit to a range of measurement problems.

From another point of view, NDT sensors for structural condition investigations are widely developed and used. In most cases several sensors are used on the same area. At a signal processing level, the use of multiple sensors can overcome the effects of signal noise (of each detector) by providing more information via different features. The author decided to develop this approach in NDT based assessment of concrete prior to repair. The detector' data provides information for different features such as resistivity and strength. Data fusion of that signal leads to fast and reliable conclusions for surfaces or a structure under investigation. Real industrial applications could reduce the time and number of measurements needed and thus reduce the cost of analysis [Automation, 2001].

6.4 Main advances in this research

The main advances achieved in this research are as follows:

- Analysis of the problem of concrete NDT measurement.
- Development of a new mathematical approach to data fusion of NDT signals for concrete measurement.

- Development of a new approximation algorithm for data visualisation using different parameters and data accuracy.
- Development of a rule-based approach (expert system) for data evaluation.
- Development and testing of data fusion software that supports decisions in concrete repair.

In signal analysis for industrial applications, several major problems in signal processing, from mathematical point of view, are tackled. The author as derived the optimum mathematical models for signal processing and performing data fusion on signals from different sensors. For comprehension of the complex process, a graphical user interface has been prepared. A prototype system has been implemented using Java Swing computer code. The system has been tested with artificial data for model stability and subsequently using real survey data.

6.5 Signal analyses from industrial measurements

6.5.1 Standard methodology applied in practice

NDT instruments have previously been introduced in chapter 3. Only some specific devices adopted in the development of the, Stage 2, approach to data fusion and those selected NDT equipment were available from the company 'PROCEQ'. These include several automated devices for concrete testing, which are presented in the following.

- Digi-Schmidt 2000
- Tico ultrasound
- Canin corrosion detector
- Resistivity meter
- Torrent permeability tester
- Protometer 5 rebar detector

On close examination of the above six devices, it is found that there are several similarities between them. All of them have a small computer block and memory that allows storage and data transfer to a PC. Similarly, they all calculate and store the mean, standard deviation, and maximum and minimum values as basic statistical data evaluation. The size of their memory store allows large surfaces to be investigated in a single session. More importantly, they measure different parameters of concrete condition.

However, analysing using the traditional approach several disadvantages are apparent. For example, in most cases separate analysis of the mean and standard deviation are not enough. Furthermore, statistically the data is incomplete and human interaction is necessary. From the author's research, the combination of different features will achieve better data evaluation and add considerable value to the gathered data.

6.6 Multi-sensor detection and data fusion

Multi sensor detection explores the idea of combining several features together to reduce the noise. This can reduce the statistical calculations necessary. It can be applied for inspected surfaces where, for some reason, sensor data is missing. Also, it might not be possible to use a particular sensor at a location, for example, very near edges. This means that data is missing at a position where other sensors give information. The pattern of the variations of these other sensors can be used to deduce the missing data. This can raise the probability of such data and increase the certainty in the fused result.

Multi sensor detection has very large applicability in industry [B. Karisson, 2002] and science. The basic idea is to derive different information via different features (for example strength) for same the object. Due to the relationship between features, deriving information for the zones with missing data by using information from the known features is possible.

This is a big advantage because in the fusion process, use of less data from a number of sensors is more reliable than using substantially more data obtained from single sensor. The following table 6.0 gives is a brief explanation:

Point of detection	Detector 1	Detector 2	Detector 3	Detector 4
A	20, 20, 10, 100, 10	--------------	------------------	-----------------
B	20, 10	30, 20 30, 10	40, 50 50, 10	100, 100 100
Related rules (Probability to be good/bad)	50%	60%	70%	80%

Table 6.0. Illustration of probability outcomes with sensors

Four different detectors were used to investigate two points (A, B) in the same specimen, Detector 1 data was available only for point A, whereas the other three detectors provide a full set of data for point B. By fusing the data from detectors where data as given by rules, and statistics techniques on the detector were data are missing, it is possible to deduce the data missing and achieve increased certainty in the final result.

However, this method does have several disadvantages, which have to be considered. The connections between features have to exist with high probability. For example, if one sensor detects cracks whilst other sensors are unaffected by the occurrence of these, they should not be uses to decide the occurrence of a crack were data is missing. This may not be a reversible condition i.e. the sensor detecting cracks may also respond to the events that the other sensors detect. The following must be taken into account, however.

The noise reduction depends on how many features are used and how strong is the connection between them in particular case.

The data has to be normalised and in many cases it is not applicable as real values (signal become virtual or relative).

6.7 Obtaining required condition for data fusion Signal Analysis

There are several schemes for creating data fusion from mixtures of parameters. Figures (6.1), (6.2) and (6.3) show these possibilities.

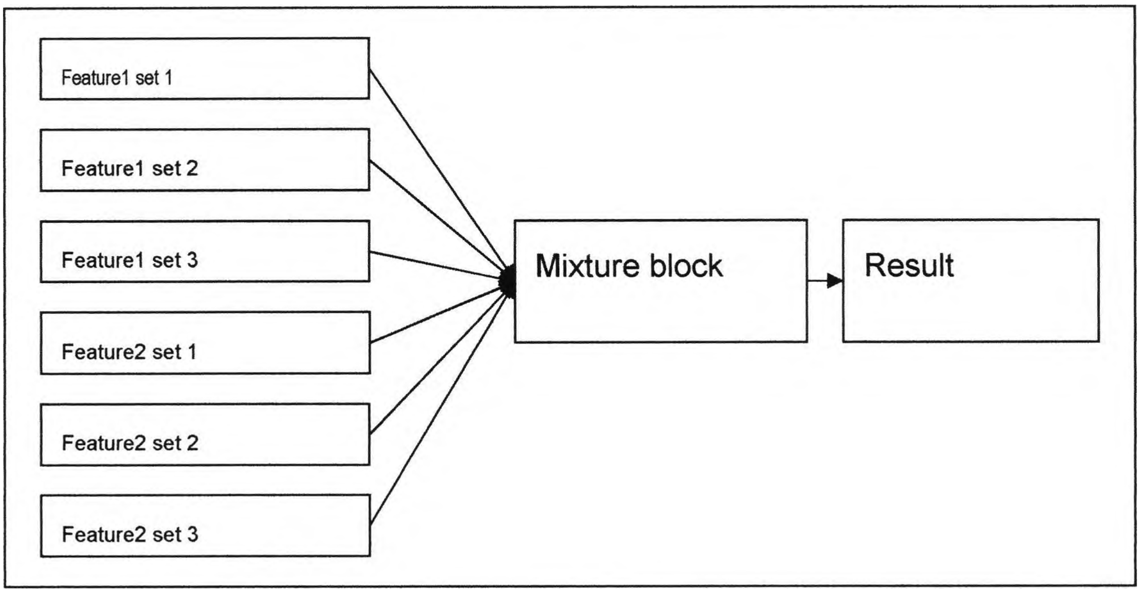


Figure (6.1) Proposed Approach for Data Fusion

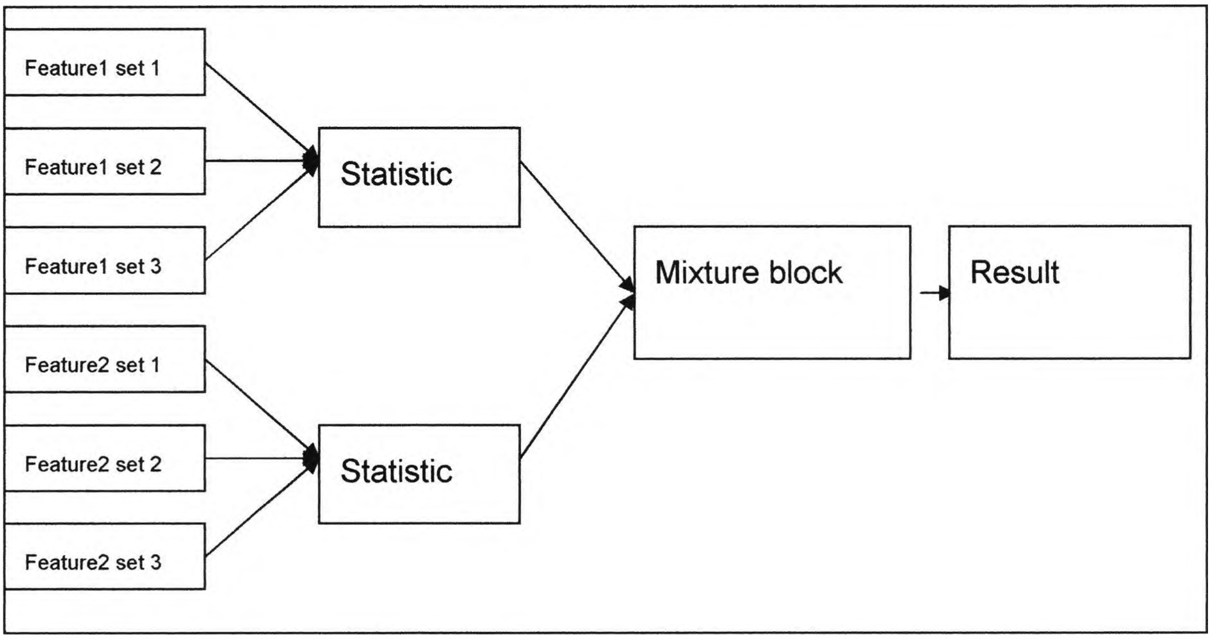


Figure (6.2) Proposed Approach for Data Fusion

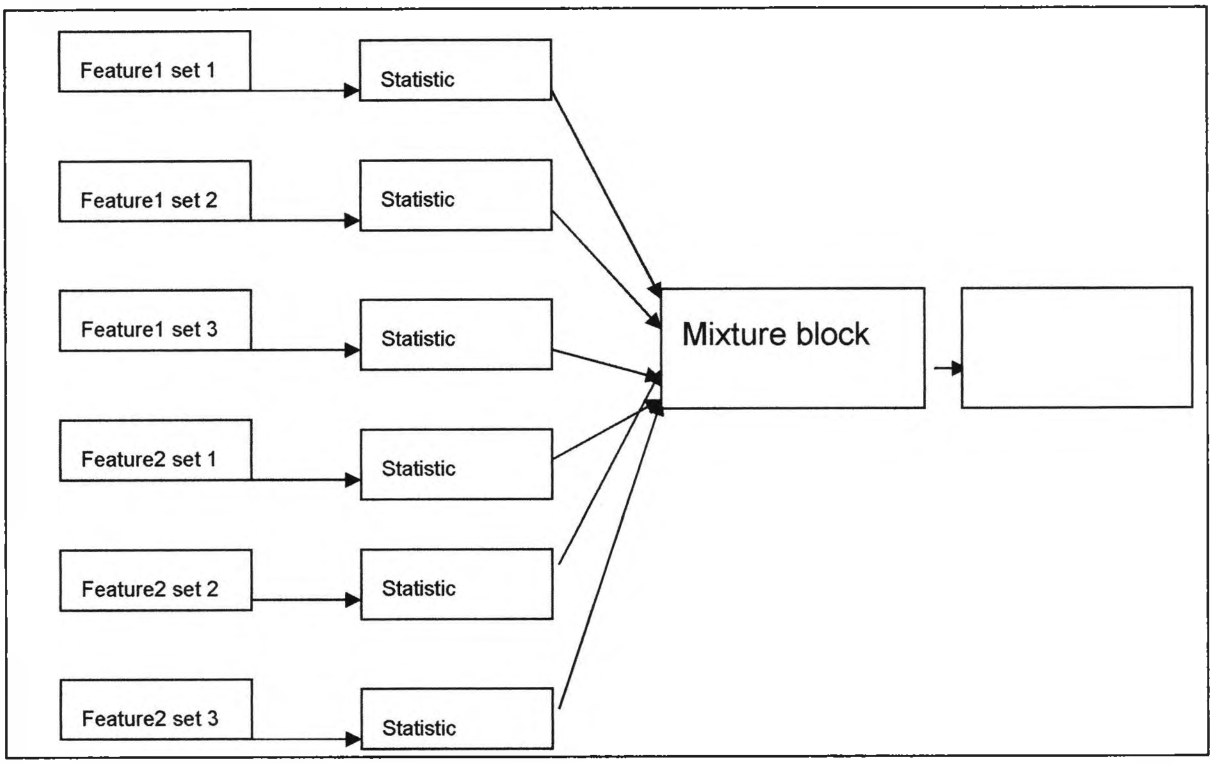


Figure (6.3) Proposed Approach for Data Fusion

At this point only these three general options will be considered, with the question as to which of them is optimal. The next table shows the advantages and disadvantages of the methods and the optimum method can be selected according to the conditions required. To decide the best variant, a point based decision table is used, with .each categorising question having answers in the following ranges:

- (7-9) best satisfied,
- (4-6) satisfied,
- (1-3) doesn't satisfied condition.

The next action is to calculate the total 'satisfaction number' and compare these to decide the best variant.

Required / expected conditions from the model	Method 1	Method 2	Method 3
Computational calculations (speed)?	9	6	3
Small Computational complexity	1	6	9
Model Stability	3	5	9
Computational precision	2	6	9
Applicability	4	8	8
Reusability of the model	5	9	9
User friendly	5	9	9
Automation friendly	3	6	9
Suitable for large amount of data	1	9	4

Table (6.0) Evaluation of Methods

In all measurements real values have been used as: seconds, number of operation, number of possible extreme conditions for the mathematical model, result precision, in how many cases is applicable, etc. The table 6.0 represents, for every method/feature result, weighted values on a scale of 0-9,

Computing the 'satisfaction number' for each scheme gives:

- Option 1 – 33 points
- Option 2 – 64 points
- Option 3 – 69 points

A similarity can be seen between options 2 and 3. The dissimilarity between option 1 and the others becomes apparent in that option 1 is the mixing block algorithm that has to handle all data (without exception or validity of that data). Integration into the model is difficult and this option is not very suitable for large amounts of data, the result not being very precise.

In conclusion, having a small statistical operation in front of the mixing block can reduce the noise and create possibilities to evaluate the data before mixing process, which means the user can monitors absolute data values from measurement and their parameters instead of relative values. This is important because the human-machine interaction becomes more human friendly and easy to understand.

6.7.1 Cost Analysis in Logic Data Fusion system

Before applying any changes in standard industrial approaches for data analyses it is a must to calculate the cost of the new approach. There are several options available that can help to clarify this matter.

In some cases, integrating part of the system in different devices (apparatus) and splitting the system physically in parts is possible. In other cases, due to system complexities, keeping the system in different computers or making it operate on the internet is recommended. An industrial system with high complexity sometimes requires different levels of access from different users. All this possibilities have to be subject to cost analysis.

In this case, it was intended to create a portable, standalone application, where the cost of the system has to be small (less than 10 000 pounds). This system should include five channels with high reusability, however, to reduce the price, it is intended to include two levels of user access (expert and guest). This will reduce the need for learning and data estimation algorithms, and finally accelerate the algorithm. Disadvantage of the system will be extra databases with rules which have to be updated by the expert. Via the human-machine interaction will be possible, at a low level, to achieve additional noise reduction.

The expected price of such an industrial application will be in the range of 8-15 thousand pounds, which make this technology applicable even for small companies. Advantages of the systems are code reusability, several channels working simultaneously, an expert knowledge database, statistics in different levels on the system and, finally, generation of the report. The author seeks to automate all the manual process in data evaluation, starting from data storage and data presentation, data evaluation, noise reduction, and final conclusion generation. In practice, such system should reduce time and manual calculations.

6.7.2 Computational time and Run-time control problems

Computational time is a significant problem for industrial systems. An important task is therefore to to reduce the computational time to a reasonable level. Usually, computation time is not associated with run time control problems. In this case, however, a one direction (forward and off-line) system, which doesn't require run-time control, will be built.

A basic problem that can occur is associated with internal calculations in graphical modules. Such problems can be resolved in several ways:

- Internal processes will be in threads overwritten by other visual process for the user.
- Internal processes will be calculated in blocks with the user having information for calculations.
- Internal processes will be performed in one thread with the user having notice beforehand.

A reasonable calculation delay must be added to the criteria in order for the model to develop. In this case, a reasonable delay is derived from external measurement process (detectors and devices). As it can be seen from the technical description of devices (detectors) several seconds to one minute delay is a reasonable delay for this system and the end user.

6.8 Data Fusion System

6.8.1 Noise analysis and noise reduction

Noise analysis and reduction are main tasks in the Data Fusion System. Analysing the source of noise is important in this case because this will have an effect on the creation of the algorithm and the methods for noise analyses and reduction. In general, noise can be internal (from the device which can be used or in the algorithm) and external that can't be controlled. Also, random and consistent noise may be relevant.

6.8.1.1 Internal noise

Internal noise is typically small and at a consistent value that can be filtered to an acceptable level. Random internal noise can appear only due to errors in the mathematical mechanism or physical data damages (missing data).

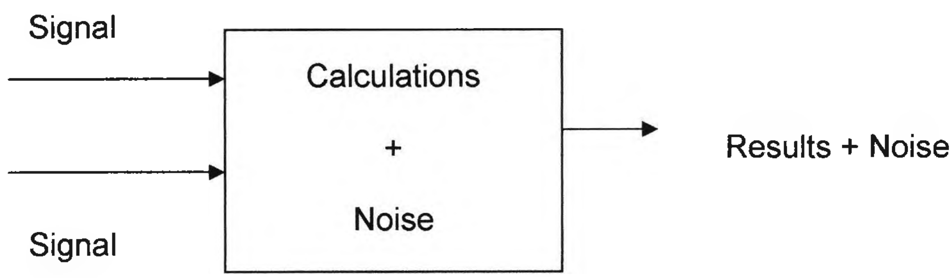


Figure (6.4) Internal Noise

6.8.1.2 External noise

Noise can be consistent or random, the first of which can be filtered depending on its nature. The second has to be eliminated and the challenge here is to operate a mechanism which can distinguish between consistent and random noise.

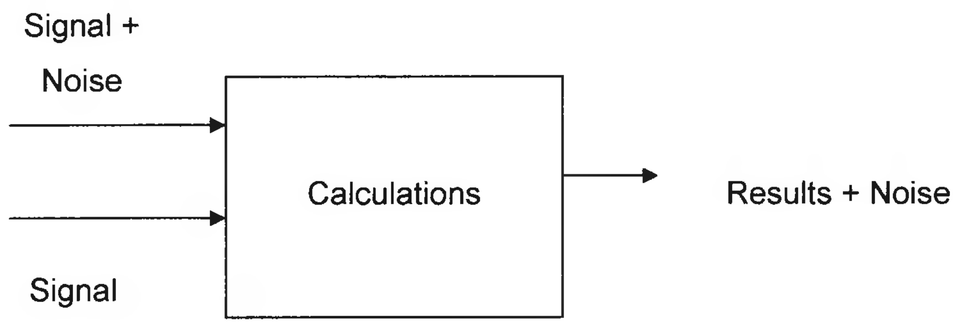


Figure (6.5) External Noise

6.9 The anatomy of Data Fusion

In order to gain an appreciation of data fusion, the "definition" of data fusion must be divided into two parts, firstly to describe the attributes of a data fusion problem and then enumerate some of the solution-techniques that data fusion provides.

6.9.1 Mathematical justification for using data fusion method for concrete condition assessment

Here, the author will introduce the mathematical approach to data fusion process. This explanation will clarify the reason behind using one dimensional representation of the data rather then multidimensional. Also, in this approach, different mathematical challenges, some of them still unresolved even from the most advance mathematical theories and approaches, will be introduced.

We assume all measurements are represented as vectors in a multi dimensional space. At the same time, every dimension will provide information for different structure's problems. For example, use of the Schmidt-Hammer will measure strength; and the Resistivity Meter, resistivity.

The question posed is what is the mathematical justification and logic for combining such data together when the results are measured in different units: resistivity in omes (Ω), temperature in degree etc? The answer lies in the logical cross-connection between all these data. By looking at the data itself, it can is clear that finding a logical explanation is not be a straightforward task. A graphical presentation of this problem is presented in figure (6.6).

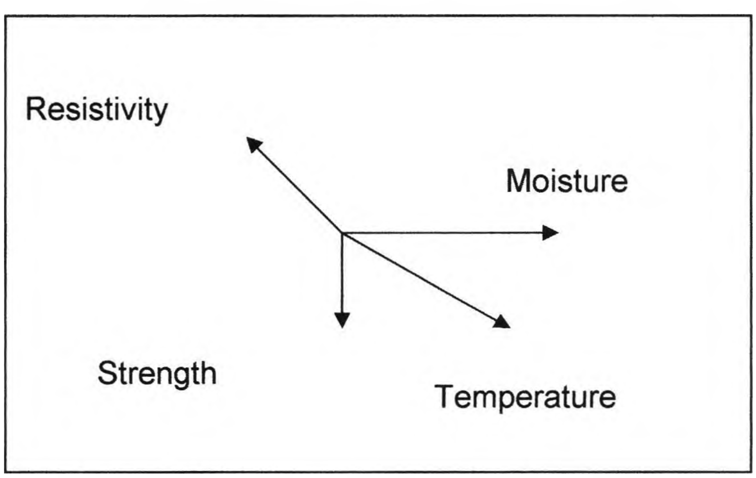


Figure (6.6) Graphical representation of the measurements in multidimensional space

Analysing these data as absolute values provides only mathematical (statistical) parameters and nothing more.

The only way to extract information for the measured surface is by using these data as relative values i.e. by comparing the known values (extracted from the standard or other experiments) and the data obtain from a measurement from particular device. The result of this comparison is a relative value which represents to some degree how good or bad is a concrete surface compared to a standard one. Such an approach will create new dimensions for every measurement. This is represented in figure (6.7) for all parameters in figure (6.6).

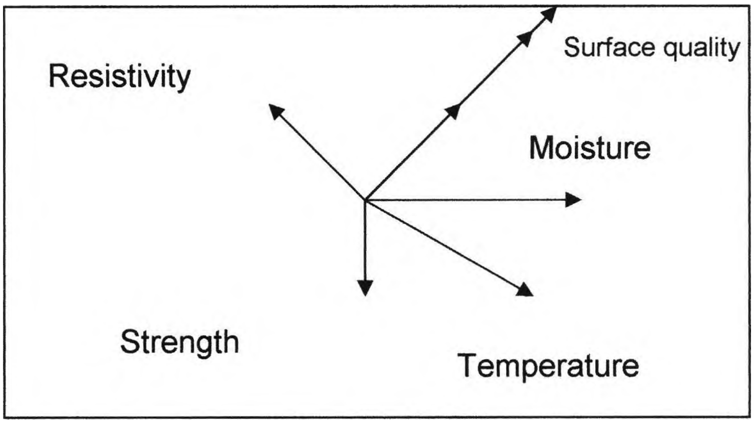


Figure (6.7) Representation of dimension "Surface quality"

This new dimensions are represented as new vectors with the same direction but different size according to the comparison result. The meaning of this is that vector direction represents the measured units (in this case % how reliable is the surface in comparison to standard) and the size the value as a percentage. Analysing this approach, every standard measurement will have a vector in this dimension. Having the same measurement scale (from 0 to 1 or 0% to 100% reliability of the surface and representation for every standard measurement) makes data fusion for this particular dimension achievable.

The only complication the user can face is after performing the fusion is tracing the reason for the outcomes, i.e. why a surface is determined to be bad or good. To analyse the reason for the result of the data fusion, the initial information the absolute data measurements for every device must be kept intact.

Having precise analyses at the initial data makes it possible to discern the reason for having a particular result or another in the model mixture. Also, this provides separate information or recommendations on reliability of this particular device measurement. The author uses this information in the decision block by creating special weighed constants for every used device. This information represents the reliability of the results from every device.

6.9.2 The problem

As explained previously, data fusion is not a particular algorithm for solving all "fusion" problems, nor it is even a suite of such techniques; it is more an approach to problem solving. Problems arise in deciding which mathematical domain is the correct one to work in for a complex problem i.e. which techniques and algorithms in a given domain are suitable for achieving a solution. Data fusion is the technology whereby often large amounts of diverse data are combined into a consistent, accurate, and intelligible entity.. There are several distinct flavours of data fusion: in some scenarios, for example, the data corresponds to different attributes of the same object; in others, the data is effectively repeated measurements of the same attribute. In the former case, the data has to be fused in an intelligent manner, taking into account the different natures of the attributes, to gain as complete a picture as possible of the object from its component attributes; in the latter cases, redundancy in the data is used to reduce errors as much as possible.

The number of algorithms that can be used for data fusion is limited only by human imagination. Within each algorithm, there may also be an infinitely many variations. For the purpose of this thesis, evaluation is according to noise reduction capabilities.

In order to make the definition of data fusion more intuitive, it is useful to enumerate some of the measurement aims for which data fusion is deployed:

- Reliability - to obtain better results than the best individual data source is capable of providing.

- Completeness - no direct way of measuring required property.
- Improvement - the need to take more factors, or influencing quantities, into account.
- Comprehension - the need to reduce information overload.

It can be seen that different measurement problems will place differing emphasis on each of the above points; similarly, different data fusion techniques will be better suited to some aims than others. Similarly, it is important to know whether the problem demands a real-time solution (such as target tracking), a batch-process, or a once-only calculation help to determine the solution technique. Assumptions might be that the relationship between measurements is polynomial (up to a certain degree), where different types of curve fitting algorithm are then suitable.

6.9.3 The solutions

Having given in the above some indication of how one might recognise a data fusion problem as such, some of the areas and techniques of mathematics that have been used to tackle these problems are now described. In the initial stages of a survey carried out by NPL, the following, not necessarily comprehensive, list of areas were addressed:

- Physical modelling.
- Empirical modelling / curve fitting [G.Farin, 1990].
- Probability.
- Statistics.
- Soft computing.
- Signal processing.
- Novel techniques.

6.9.3.1 Physical modelling

In this group are the techniques that exploit a prior understanding of the behaviour of the system being measured and the relationship between the attributes being measured. In such circumstances it is difficult to see where data fusion can play a defining role. However, if the prior understanding is not certain or comprehensive, then this physical modelling will have to be supplemented with other mathematical techniques, and the data fusion then becomes less trivial.

6.9.3.2 Empirical modelling

In this situation, little or no direct physical knowledge of the behaviour of the system is known. Generic assumptions about the measurements are required and fitting of the observed data to these. Typically, these case starts to draw conclusions about relations in the data without too many prior assumptions or intuition understanding of the system. Traditional statistical techniques for a variety of tasks subsidiary to fusion may be used. For instance, it is possible to use tests and analysis of variance to help determine the presence of a faulty sensor within an array of other sensors, or by using analysis of covariance to help decide which measurements are interrelated and which are directly linked to these measurements. This information can then be taken into account when deciding which measurements (or measurement devices) are significant.

6.9.3.3 Soft computing

These techniques are traditionally used to achieve artificial intelligence. They cover the areas of artificial neural networks (ANNs), genetic algorithms, and fuzzy logic, amongst others. ANNs might be used to learn how a series of past inputs to a system related to its outputs, and then use this "knowledge" accurately to fuse present inputs in order to predict an output. Fuzzy logic can be used as a way of representing knowledge of a system that is more qualitative than would be the case with physical modelling.

6.9.3.4 Signal processing

Signal processing can be thought of as a subset of physical or empirical modelling. However, the problems posed by fusing many real-time data streams, such as their synchronisation, taken together with the fact that these techniques are often not familiar to those outside the signal processing fraternity, has encouraged the author to give the subject its own heading. The

Kalman filter is one of the best known signal processing ideas within data fusion. This technique allows reconciliation of many measurements of the state of a dynamic system with predictions of the subsequent state (predicted by some physical model of state evolution), each being weighted by some indication of the source's reliability, in order to achieve the best predictor of that state.

6.9.3.5 Novel techniques

These techniques those are difficult to place elsewhere. Over time, it is likely that similarities will be seen, either amongst these techniques, or between these and those in the above categories. An example of a novel technique is Dempster-Shafer theory. This is in many ways an alternative to the usual probabilistic description of uncertainty. Sensors have a prior level of confidence and provide a measurement result with this confidence. Multiple sensors can have very different confidence characteristics (for example, sensor X is reliable in the x-coordinate of a two-dimensional measurement but not in the y-coordinate, and sensor Y is the converse). These characteristics are taken into account when the measurements are fused according to the Shafer rule of combination. One of the primary advantages of this approach is that it can deal consistently with a sensor that claims to be ignorant of a component of the measurement. This can be useful in diagnosing, and potentially dealing with, conflicting data sources.

6.9.4 A candidate data fusion paradigm

The above discussion indicates that there are a variety of problems and approaches to their solution as can be classified as data fusion. In an attempt to develop a framework for data fusion, therefore, it necessary to abstract the common threads running through the previous sections. It is possible to say that: "Data fusion is the technology whereby often large amounts of diverse data may be combined into a consistent, accurate, and intelligible whole" and as a rule of thumb, to help the users recognise data fusion before presenting a working version of a paradigm for the data fusion process. A traditional approach to solving a problem might be to process all the data with an algorithm of good reputation, the reward of which is the calculated result. Another approach might be to look for relationships and hidden patterns within the data would result in increased knowledge about the system which produced the data. It is the author's contention that a data fusion approach will often take aspects of both these approaches. It seems that many data fusion implementations in the past has been used in data processing, as an intermediate step of extracting knowledge of the system from the data and using this to enhance data processing. This is perhaps illustrated by a toy example. Assume that there are several sensors measuring the same sequence of random binary digits (0, 1), but are known to make errors (that is, to report the flipped the value). The error rates are not known beforehand but a person can assume (prior knowledge) that they are small. A simple non-fusion approach would be to take the majority decision of the sensors as the estimator of the true value. If a person was allowed a training session, with the outputs of the sensors recorded for known values of the input, then the user could start to gain some knowledge of the sensors' reliabilities, and then use this for data processing within the system. It has been observed that this approach is a better estimator than the majority verdict, which, is in turn, is better than the best individual sensor. Even if no training is allowed, it is conceivable that a better strategy than majority-rule could be developed as it becomes apparent that certain sensors are frequently different from the majority verdict. Therefore, to achieve the ultimate fusion solution to a given problem, it will be necessary to mix techniques so that the correct balance of knowledge acquisition and processing is achieved. Thus it is seen that data fusion is never going to eliminate the need for careful design of the way measurements are handled.

6.9.5 Noise reduction methods by Data Fusion

Development of two different approaches mixed into one system is the main objective in this case. The purpose for this is to reduce the amount of calculations and thus accelerate the system. An experimental, unsupervised approach will be developed and also an analytical supervised approach. Combining them into one system will be achieved by using the advantageous aspects of the two approaches.

6.9.5.1 Decision rule based system

This approach relies on a knowledge base and a decision system can be created if rules and prepared decisions for these are available.

Creating the rules and connections between them is often the most difficult aspect of the approach. Usually, rules are categorised and a special optimisation function uses only part of them or special combinations of them. It is not obvious that the use of a given number of the rules results in a particular answer probability. At some stages, introducing too many rules can overcharge the system and reduce the probability of the answer. Rules represent a discrete situation so the answer is probabilistic and, at some stages, because of the lack of knowledge, approximation is introduced into the result. The advantage of this method is its simplicity and the disadvantage the needing for stored knowledge and rules that must be created by an expert.

6.9.5.2 Statistical methods

Statistics offers a powerful mechanism for data analysis and data evaluation. Taking into account that the data is poor (the data is insufficient for high precision statistical evaluation), a simple statistical model presentation will be explored. In this the rule of 'goodness', in a statistical sense, is derived from n measurements. If for some data $n>30$, then it can operate to a high statistical approximation (probability>70%). According to the standard deviation, it can calculate the 'goodness' value in statistical sense.

To derive variance and simple mean are requirements in determining standard deviation. Variance, which is a measure of how spread out a distribution is computed as the average squared deviation of each number from its mean. For example, for the numbers 1, 2 and 3 the mean is 2 and the variance is 0.667.

Formula for mean is as follows:

Mean of

$$X = \mu = \sum_{i=1}^{n} p_i X_i \qquad 1$$

Where; n is the number of values of X and pi the probability of the occurrence of value Xi.

The formula for variance is as follows:

$$\sigma^2 = \frac{\sum (x-\mu)^2}{N} \qquad 2$$

Where; μ is the mean and, N is the number of scores.

The variance is computed as:

$$s^2 = \frac{\sum (x-M)^2}{N} \qquad 3$$

Where M is the mean of the sample and S the Standard deviation

S is then a biased estimate of s and:

$$s^2 = \frac{\sum (x-M)^2}{N-1} \qquad 4$$

Representing the unbiased estimate of s^2.

Probability distribution is also an important parameter in statistics, Gaussian distribution being a typical example. Most data in nature is distributed and calculated in this distribution. The use of Gaussian distribution is widespread in industry mainly because of mathematical simplicity:

$$p(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2} \right] \qquad 5$$

The graphical presentation of this distribution can be seen in figure (6.8).

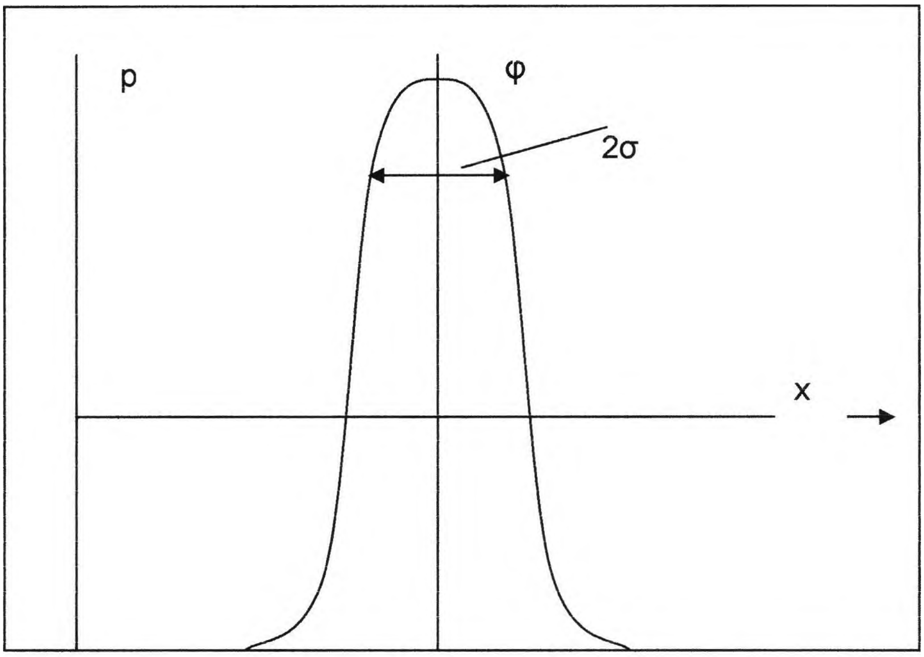


Figure (6.8) Gaussian distribution

The standard deviation is often used by investors to measure risk, for example. In this case, the basic idea is that the standard deviation is a measure of volatility: the more a stock's returns vary from the stock's average return, the more volatile the stock. To illustrate this (table 6.1), we consider two hypothetical stock portfolios and their respective percentage returns over six months (see data table below). Both portfolios end up increasing in value from \$1000 to \$1058, however, they differ in volatility. Portfolio A's monthly returns range from -1.5% to 3% whereas portfolio B's range from -9% to 12%. The standard deviation of the return is a better measure of volatility than the range because it takes all the historical data into account. The standard deviation of the six returns for portfolio A is 1.52; for portfolio B it is 7.24. This idea can easily be related to data collected from sensors.

	A	
Value	Return (%)	Final Value
1000	0.75	1008
1008	1.00	1018
1018	3.00	1048
1048	-1.50	1032
1032	0.5	1038
1038	2.00	1058
	B	
Value	Return (%)	Final Value
1000	1.50	1015
1015	5.00	1066
1066	12.00	1194
1194	-9.00	1086
1086	-4.00	1043
1043	1.50	1058

Table 6.1 showing value & return

6.10 Combined Data Fusion approach in computer-human interactions system

6.11 Simple solution and skeleton

As previously concluded, developing a combining approach will be advantageous. However, to choose the best approach, initial calculations are performed in term of the requirements. It is possible to develop further the conclusions from section .6.3: i.e. obtaining the required conditions for data fusion Signal Analysis".

The author now introduces into the system more restrictions regarding the type and evaluation of data. Calculation of the standard deviation statistic requires a minimum data set of 5 measurements. Also, for data fusion at least 2 different measurement features are needed.

It was decided to also a build rule based approach for final data fusion decision. For this, at least 2 decision splitting rules, filed into 3 patterns, are required (unclassified data as a pattern must be always considered).

Supervised or unsupervised approaches to data fusion result evaluation are required in the decision machine.. In the supervised case, the author has to consider how to update the data base with knowledge, and decide what type of decision rules is applicable. In the unsupervised approach, the necessary level of system interaction (how deep the user can control the automatic process) must be evaluated. Having established all this information, deriving an initial scheme of the system is possible.

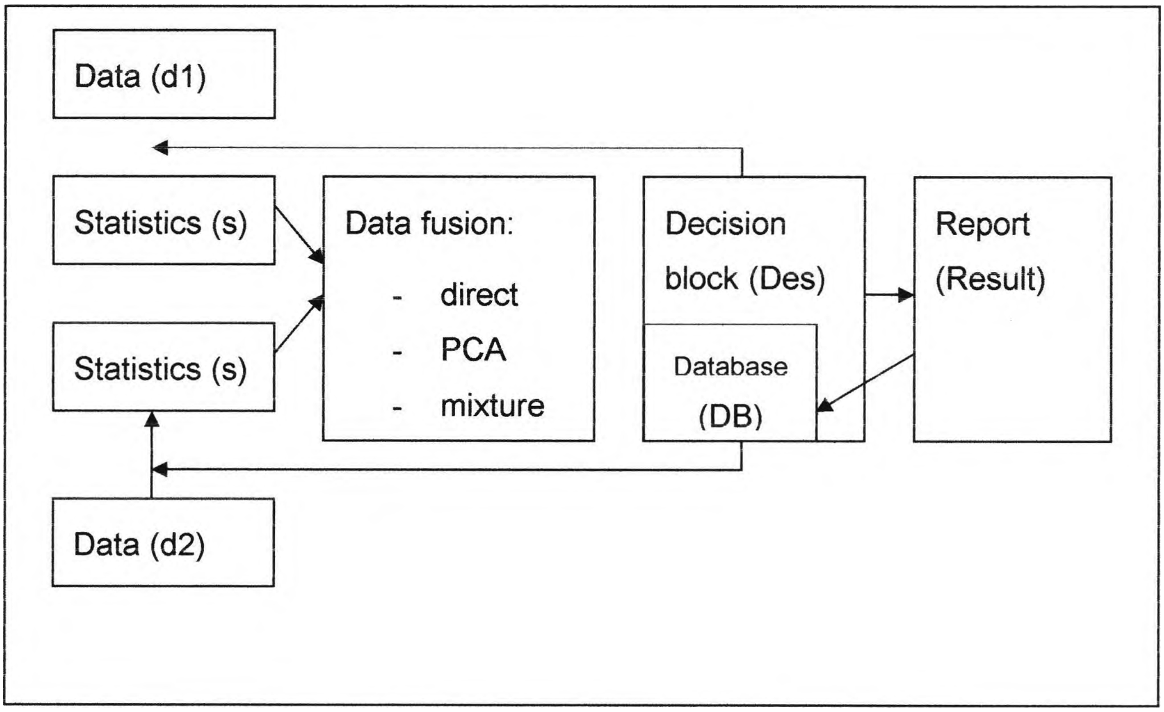


Figure (6.9) Simple Data Fusion System Skeleton

Analysis of figure (6.9) shows that the Decision block is complicated because of the many connections and back signals. The processes in figure (6.9) are an iteration step algorithm for best matching in the database (in probabilistic frame). This means that the more steps the user performs the closer to the real is to the correct one. Logically this is true but not mathematical in the sense of being a reasonable result.

According to the parameters it controls in the back signal, there can be 3 situations in the step algorithm:

- a) Oscillation and decreasing,
- b) Second order curve to the best match
- c) Linear relationship

In practise, the best are b) and c). Situation a) can be considered only if the initial conditions are changing over the time and the algorithm follows the changes.

It is not important to go into details in these approaches, many of which are explained under 'Tracking algorithms'. Instead, the author concentrates on the decision block.

The basic process of extracting a decision can be expressed as:

$$\mathrm{Re}\,sult_{stepj} = \mathrm{Re}\,sult_{step(j-1)} + F_{datafusion(stepj)}\left[K_{total}\sum_{x=1}^{m} K_{x} f_{ststistics}\sum_{p=1}^{l_x} d_{p}\right], \qquad 6$$

where Result step J is a result from the system in step j, F data fusion step j is a result from data fusion block in step J, K total is a total coefficient which control the back signal dependency (and according to the requirement has to control the speed of adjustment) and Kx the coefficient derived from database and control feature dependences.

6.12 Rule based algorithm

The rule based algorithm concentrates on several important points:

- keeping and managing the database with knowledge
- generating the coefficient of reliability of every feature
- building or proposing the final decision in text form
- maintaining the stability of rules and their connection

A supervised approach in the rule based algorithm is adopted. In this, users (experts in field of measurement) create rules and maintain the connections between them. To accelerate the system, this process has to be user friendly and easy to code, especially taking into account that the user cannot be expected to be a computer programming expert. The system must use different rules for different situations and, for simplicity, this requires more than one data file that the user has choice over.

Related factors to be considered in building the rule based system, which concern the NDT equipment used, are considered in the following:

6.12.1 Operational factors concerning individual sensors

6.12.1.1 Schmidt Hammer

Operational factors concerning the Schmidt Hammer are:

- Values increase slightly with increasing moisture content.
- Value extremely high if target is a shallow stone particle.
- Values tend to be unreliable on rough concrete.
- Needs regular calibration.
- Tends to overestimate strength on heavily carbonated concrete (age of structure and exposure is important here. New structure would give lower values than older structure for equal concrete strength).
- Unable to repeat readings at exactly the same spot (use small pattern of points because surface gets damaged with impact of hammer).
- Angle to surface matters, so some user experience is necessary.
- Useful in a relative sense rather than absolute strength measurement.
- Can give high values if used directly over shallow reinforcing bar.

6.12.1.2 Covermeter

Operational factors concerning the Covermeter are:

- Unaffected by moisture content, generally very accurate.
- Cannot detect very deep reinforcement very accurately in respect to diameter.
- Unreliable in detecting difference between pairs of bars and large diameter bars.
- Affected by aggregates with metallic content (ferrous).
- Accuracy and performance range differs considerably between different types of covermeters.

6.12.1.3 Half Cell

Operational factors concerning the Half Cell are:

- Indicates likelihood of corrosion activity, not actual corrosion activity.
- Does not tell rate of corrosion.
- Affected by level of moisture content (extremes of very dry and very wet are to be avoided).
- Can be used in absolute way or relative way (more reliable of two options).
- Affected by amount of reinforcement and its depth from surface.
- Needs connection to steel (slightly destructive).
- Reliable under appropriate conditions.
- Not affected by age of structure unless salts are applied.
- Is affected by chloride contamination (ions for electrical current. This means that the type of structure matters e.g. bridges, car parks and roads have de-icing salt applied. Also age is important because salt effect is accumulated over time).

6.12.1.4 Resistivity Device

Operational factors concerning the Resistivity Device are:

- Indicates actual corrosion activity and is only used in absolute sense.

- Otherwise same as Half Cell factors above.

6.12.2 Other Factors

Other factors related to the structure itself are as followed:

- Age of structure can matter e.g. reinforcement content and cover varies with design epoch
- Exposure of structure always matters e.g. temperature average and extremes, freeze cycles, humidity, wet/dry
- Location matters (e.g. industrial pollution-acid rain or marine environment with air salt)
- Purpose of structure matters e.g. bridge, car park, marine all subject to salt.
- Loading history e.g. earthquake, flood, overload etc
- Type of construction e.g. pre-cast or cast in situ
- Quality of construction workmanship
- Special circumstances e.g. unusual aggregates or chemically active aggregates/sand.

6.12.3 Statistical engine

For the statistical engine, it is possible to explore the simple mean and standard deviation of the data. An important requirement for this particular statistical engine has to be exclusion or changing data. This gives the possibility to evaluate the data without noise (excluding the noise from the process of statistics). This is a sensitive approach and it is important to take in consideration how the noise is to be measured. One method is to operate a confidence region around the mean of the data. Also, according to standard deviation, the user must be able to change the local data coefficient and, according evaluates the data changes accordingly.

6.12.4 Human machine interaction

The author decided to perform a combination of statistical and rule based approach. These naturally different approaches for data evaluation can be connected in many ways. One advanced approach to do this is in computer-human interaction system. The advantage of such a system lies in reducing the subjective factors to a minimum (exploiting the computational power of a computer) and increasing the result probability. In many ways, the human brain can perform better optimization than a machine. The only condition for this is that data is represented in proper format, easy to understand and evaluate. A further consideration is that, unlike with graphical or sound presentations, numbers often mean nothing to the user. These observations have been taken into account in building the experimental software system.

6.12.5 Required resources

In considering the development of any software, it is important to understand the precise resource requirements. For the research it was decided to develop a standalone application that allows full freedom in the choice of network. At same time the author intends to develop a platform independent application. This means that the installation has to detect the user's platform and automatically, properly install the application. The complication of such a system becomes high if human-machine interaction is allowed.

Whilst menus, buttons and other attributes are widely developed and standardised in Microsoft Windows, use of different platforms is a challenge. Also, databases and input-output communication are different on different platforms. The basic idea behind this requirement is that the user is free to use different platforms.

The requirement resources can be split into the following categories:

- Technical
- Software
- Statistical engines and mathematical methods

Technical recourses can be considered as an external computer where the software is stored. Also the possibility to transfer the data from the measurement device to the computer is required. Software resources include: software language, deploying resources, GUI and environments for creating and debugging software [J. Builder, 2000].

Statistical engines and mathematical methods are the most important part and they include all mathematical modules and classes which are used, and all graphical transformation and data presentation. Using all these resources make possible the creation of a small system for data fusion, which is organised in the way as explained in previous chapters.

6.13 System prototype Implementation

6.13.1 Block-schema of the system

Including the conclusions and initial requirement according to figure (6.3) and figure (6.5), equation (1), table (6.1) and point 6.2.3 we can draw a block scheme of the system. This system can be split into three parts according to the level of data evaluation:

6.13.1.1 Preliminary data evaluation

This includes basic conclusions for all data, estimating a devices weight for component mixing, removing or evaluating statistical data representing the sub-pattern and device signal stability. Also, at this point, the subject of information transfer to and from the system must be considered. Furthermore, the system should allow the user to go in both directions i.e. forward and backward into calculations.

6.13.1.2 Low level statistical evaluation for every point

This will include statistical evaluation for every point (in which measurements were available). Before mixing data, this engine allows fine noise filtering and data evaluation. Interaction of the user at this point is important because, after mixing the data into this model, the error is smoothed and difficult to extract and remove. Also, this level has to allow the user to compare global conclusions (data evaluation) with local. Even more important is user interaction because if there are statistical errors (shifted data) for one point only in some device, it is important for this to be apparent so that the user can react according to the situation.

6.13.1.3 Approximation methods and recourses

It is impossible to measure extensive surfaces with very small discretisation. At the same time, it is necessary to explore visual presentation of every point into the surface in case the user is interested in such regions. An appropriate algorithm will be able to approximate every point having information for the measured point from other devices.

6.13.1.4 Mixing block

The basic idea in the mixing block method is to reduce the dimensionality of data representation by evaluating every mixture parameter according to their importance. This can be presented mathematically as:

Every device field is

$$F_{device} = \begin{pmatrix} p_1(x,y) & \dots & p_n(x,y) \\ f_1(x,y) & \dots & f_q(x,y) \end{pmatrix}, \qquad 7$$

Where p(x,y) is a function representing the measured point probability and f(x,y) the virtual point with an approximated value derived from p(x,y). The mixed field can be presents as:

$$Total_{mix} = k_n \sum_{features=1}^{f} K_{feature} F_{device}, \qquad 8$$

Where K^n is a normalisation coefficient, K_f is a weight for every device (feature) and F_{device} the device field.

As it can be seen that the final field presentation does not include any information for a particular device and thus any error cannot be evaluated properly. At the same time, the model mixture collapses the feature space into one dimensional space, which can be easily graphically presented. The result is normalised giving the user possibilities to perform global pattern analyses.

6.13.1.5 Global data evaluation block

This has to give the possibility to evaluate data according to different rules, which we can modify. The purpose is to compare the global and local data presentation with this model mixture. If for some reason the area in this model mixture is marked, it has to appear in the local evaluation data. This can show perfectly what is wrong with the data in the low level ($p(x,y)$) analysing of the points.

6.13.1.6 Report and final text editing

This includes a data collector mechanism, which collects the data from the experiments, the results for which are set in the final conclusion. Also, the possibility to save and edit this information has to be developed. All these possibilities are presented in figure (6.10).

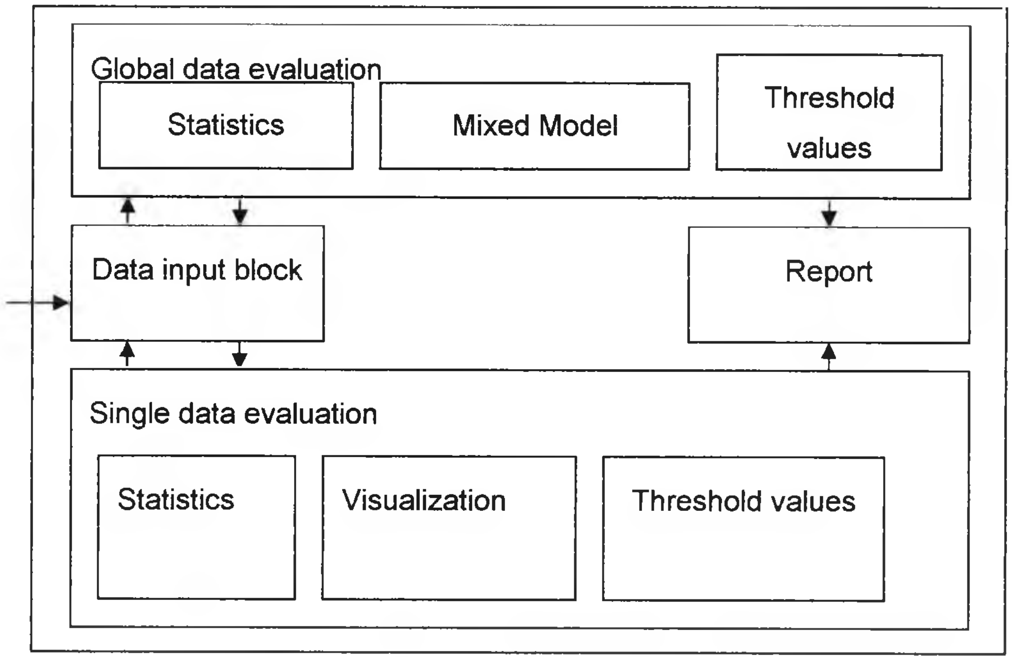


Figure (6.10) Block-Schema of the System

Figure (6.10) represents more clearly this particular approach to data evaluation in terms of computational and data handling viewpoint.

The data block, which consists of real data, has to be represented and global and local data evaluation for noise reduction included. This is the initial task in using model mixtures in data fusion. Also, in figure (6.10) possibilities for data modification, which is allowed at a local level, can be observed. This involves the user in the decision process, accepting directly data correction. The system has a resolution controlling mechanism, allowing the user to evaluate data at several levels with graphical presentations.

At this point it must be concluded that the human interaction system is complex because it allows the user to directly control the process. Such a system requires several data representation mechanisms. The advantage is reduced noise and the impossibility for abstracting the final decision, which in the industry is with primary importance.

6.14 Functionality and Software approaches

Regarding the system requirements it was decided to develop it in Java Swing [R. Eckstain, 2002]. Java [D. Flanagan, 1999] is a platform independent computer language and that permits high level object oriented programming. Swing allows the users to create graphical objects and to achieve effective machine-user interaction.

The system functionality in Java depends directly on class functionality. Fortunately, over several years Java language has had world wide development according to functionality. Sun, Borland and Microsoft have different classes available on the market.

Sun as a Java developer has several stable free versions (JDK) available on the market. For this particular application JDK1.4, was adopted. The use of classes allows us to perform such basic operation as graphical output, text boxes, buttons and Forms. [J. Knudsen, 1999]

It is a challenge to develop the application required for the described experimental work. For example, there are several approaches for creating the GUI and support system for SWING in Java.

After confirming the requirements, the system was split down into eight logical parts:

6.14.1 Load advice

This loads the expert file from the database. The file has to be editable (from human) and readable and understandable by the system. It supplies the system with rules for the rule based approach.

6.14.2 Edit file

This is the place where the expert can evaluate and edit the expert file with knowledge, rules and advice.

Proposal: This is the place where the user explores the rule based approach to extract information from device dependences in the model mixture. This can be performed by introducing a weight for each measurement device used.. The performance of the rule based system can be a choice based system.

6.14.3 Load data

Here is the place where the users load their real measurements from devices.

Statistics: The statistical block introduces different statistical mechanisms (global and local) for data evaluation and gives the possibility for data editing.

Visualisation: The visualisation mechanism has to output the mixed model result in a graphical mode. Approximation algorithms calculate and present different data according to the used model. This possibility is important for the user, because applying several approximation mechanisms will have an effect on data presentations.

6.14.4 Abnormality

The abnormality section includes several options for data evaluation using parameter thresholds. Global and local analyses are included and the value of threshold can be changed.

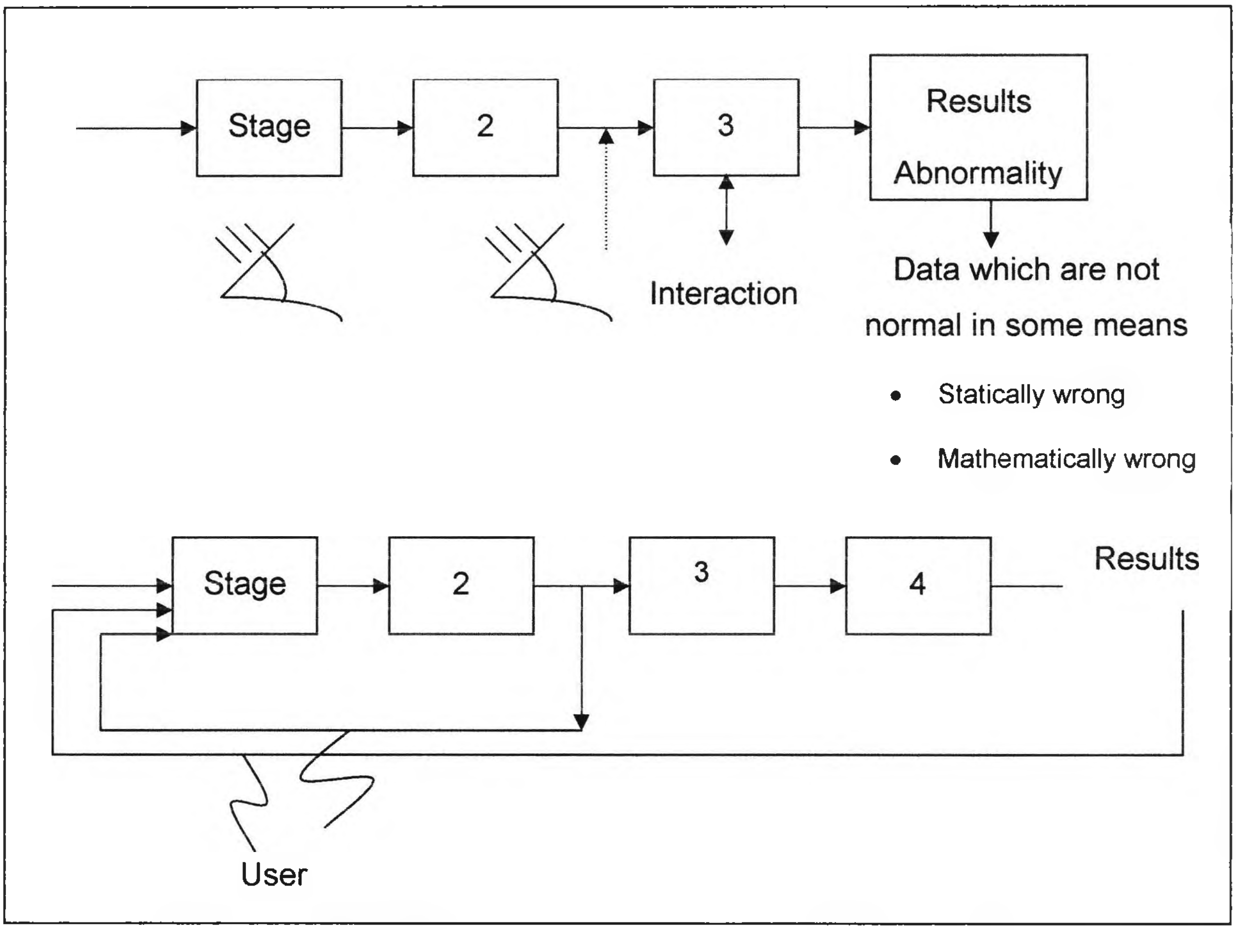


Figure (6.11) Abnormality Illustration

6.14.5 Report

Finally this section collects the experimental data and results from all experiments. An editing capability should be included and with the possibility to copy and paste this document in a DOC file. As finalisation operation creates the final decision according to the experimental data.

6.15 Java classes' usability

The best way to deliver appropriate functionality is by several screens split by the 'so called' 'jTabedPanel' method. This allows the user to know which process the system is performing. The loading operation is held in a 'jFileChooser' class, with all input and output operations requiring 'jField' or 'jLabel' labelling. For all text operations editing possibilities in the 'jTextArea' and jTextFiled' areas is also needed. Use of radio buttons or buttons for the graphics 'jPanel' is possible. All this functionality exists in Java Swing and it must be combined and used in a way to present the information in the best way to the user.

For simplicity the input/output files are chosen to be text files. In more complicated approaches using XML, External Mark-up Language, "XML" which is world wide compatible standard for information transmission, may be possible. A big advantage of SWING is the possibility for it to be loaded as server application. This means that standalone applications can easily be transformed into server applications that can support many users.

6.16 Algorithms' challenges

Several challenges were faced in the production the experimental application software. There are many technical and logical issues which needed to be optimised for the system. Here, rather than commenting on all code, only those parts which are unusual or complex are reviewed in detail

6.16.1 Logical challenges

Parsers for input files: The parser for input files are an important aspect. They have to be robust and accurate enough in terms of stability from the input. Many files are manually controlled and any small mistakes can halt the system. To deal with this, it was decided to use tokens and special symbols for marking the important parts. As an example, one EXP file which generates buttons ,[J. Biggs, 2001] [T. Tesseier, 2001] in the system can be seen.

```
Concrete
Water covered, Open building, Covered building
Water affects resistivity increasing the values and the risk of
corrosion.&0.5,0.4,0.3,0.1,0.2;Wind and water increase concrete
damage&0.3,0.3,0.2,0.1,0.1;3
Steel
Open, several flours, covered
1a; 2a; 3a
```

Figure (6.12) Configuration Files in Rule Based Approach

Figure (6.12) shows the initial information prepared for parsing. The system has to convert this into two buttons (Concrete and Steel) with optional sub-options. The Concrete button will have 3 sub-options (water covered, open building, covered building). If the user chooses the first option (water covered), the message will appear and the weight for the devices will be stored. The parser in the system is organised as follows:

Every General Button option comprises 3 paragraphs:

- The first paragraph is the button's name,
- The second paragraph are sub-button options,
- The third paragraph is the result of activating the sub-buttons,

The third line is combined from the answers of the sub-buttons with a splitting operator (;). Every answer consist of 2 parts (text + weight for the device used) with separating operators (&), the weight constant are separated by (,).

This logic is applied when the user parse the file. It is possible to include checking and error handling functions, avoiding this in purpose is for simplicity.

6.17 Mathematical challenges

Apart from the logical complexity there are mathematical challenges which require comparison of different mathematical approaches. As an example, an approximation algorithm for surface creation from random measured values will be presented. The problem is how to create a blanket surface of given density having several known points which are not part of the mesh? [T. Schreiber, 1991]

In practice, this problem is widely applied in GIS systems. Unfortunately, in most of these models they used a mesh for the initial points which differs from model under consideration. Using a mesh is not optimal in this case because it is not possible to force the worker to make measurements at fixed points. This is difficult, and in some cases is impossible because of occlusion or impossibility.

For his system the author developed new approaches and evaluated the result in 7 different ways. This also helps the user in choosing a appropriate approach for data representation and evaluation. There are approaches which can be distinguished according to the splitting rules.

6.17.1 The closest points

This is a simplest approach and for classification it uses:

$$V_{new}(x, y) = V_{measured}(x1, y1), \quad 9$$

Where;

$$(|x-x1|)+ (|y-y1|) = min \quad 10$$

The closest two points can be calculated as;

$$V= \frac{V1+V2}{2} \quad 11$$

6.17.2 Other algorithm approaches

The other algorithm approaches are:

- The closest 3 points
- The closest 4 points
- Approximation using 2 points
- Approximation using 3 points
- Approximation using 4 points

These algorithms are reasonably stable when the initial data is in a mesh form. They create more a robust and precise model which combines the value of the point with distance rather than simply ignoring the distance and performing just middle value method.

The method works with some initial assumptions. It is assumed that the value of some point from the field (Vx), depends on the existence of neighbour points. . With increased distance to some point as less affect the value of that point has. Initially, it was decided to create computer code for the 4 existing points method but later it decided to include the 3 and 2 existing point approaches.

Mathematically, the process combines geometrical measurements for the distance with a real value of the existing point. For further clarification a simple case is presented in figure (6.13) where A & B are existing points and X is the point for which the value is required.

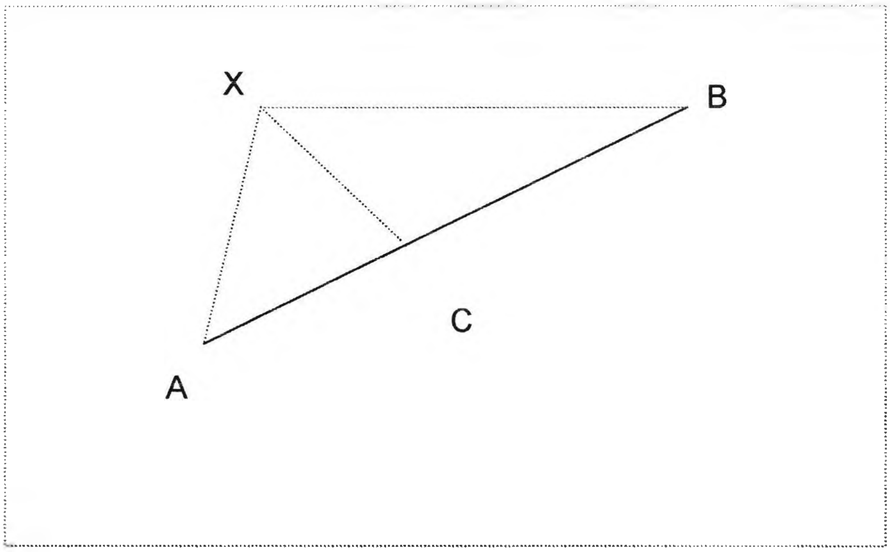


Figure (6.13) Approximation Problem from two Points

For this we can form the equation:

$$Vx = \begin{cases} \min(V_a, V_b) \le V_x \le \max(V_a, V_b) \\ V_x = V_c \begin{cases} p.C \in \overline{AB} \\ \dfrac{AX}{XB} = \dfrac{AC}{CB} \\ AC + CB = AB \end{cases} \end{cases} \qquad 12$$

The approach to combining the values with distance as is shown in figure (6.14).

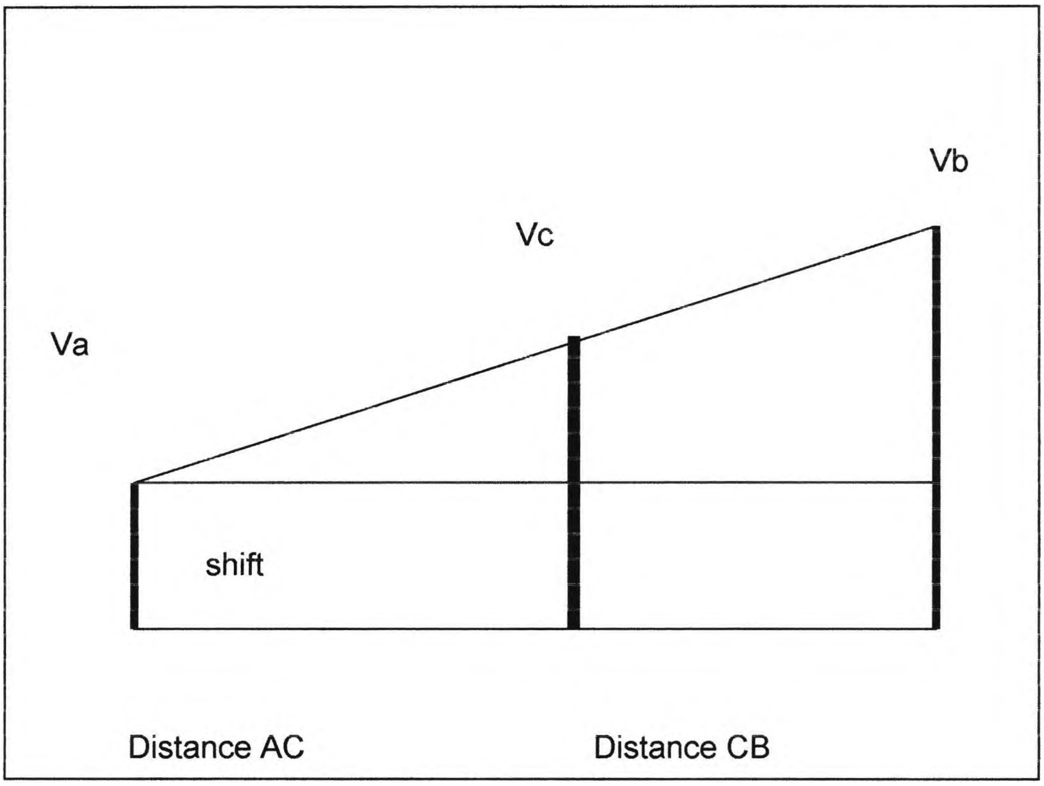


Figure (6.14) Distance-Values Calculation Problem

The location of point C can be found as:

$$\frac{y_c - y_a}{y_b - y_a} = \frac{x_c - x_a}{x_b - x_a}$$
$$AC^2 = (x_a - x_c)^2 + (y_a - y_c)^2 \qquad 13$$

These coordinates are important in calculations for more than 2 points (3 and 4). The iteration mechanism makes the calculations of each the new point until the difference between the values for the new points is acceptably small.

As shown in figure (6.15), the search of the point X, from points A, B and C, can be presented graphically as a spiral.

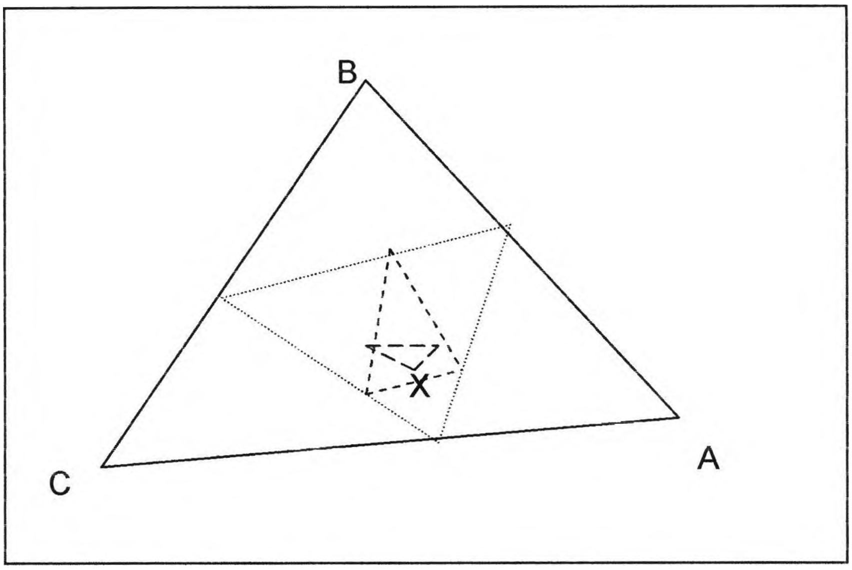


Figure (6.15) Iteration Algorithm in Point Value Search Problem

6.17.2.1 The Algorithm

Let V(x,y) will be a point from the area in which the value is required. An Iterative search is made between the available points to discover the two closest points Va(xa,ya) and Vb(xb,yb).

The shift value is calculated as:

$$shift = \min(Va, Vb),$$

where Va and Vb are values of points A and B.

With the condition that

Va>Vb, then V(x,y)= $\dfrac{(Va - Shift) * dis\tan ce(V(x,y),B)}{dis\tan ce(V(x,y),A) + dis\tan ce(V(x,y),B)} + shift$ 14

Else

V(x, y) = $\dfrac{(Vb - Shift) * dis\tan ce(V(x,y),A)}{dis\tan ce(V(x,y),A) + dis\tan ce(V(x,y),B)} + shift$ 15

We now consider the complication in using 3 or 4 points. When using 3 points (same for 4) there will be 3 possible answers which probably will not be the same because of the approximation distance/value. The algorithm has to accept these 3 answers as the initial three points and then repeat the calculation. Every calculation is with small distances between the point and the existing (calculated) virtual points. After several iterations, the 3 points will be geometrically close to the point V(x,y), and the approximation value will be with less difference. The finial outcome is that very close points are arrived at to the point where values are almost equal.

In practice, thresholding is introduced to reduce the number of calculations.. The result from these calculations is a precise data field smoothly covering the existing points. The initial existing points are presented in figure (6.16) and the result from the algorithm (using 4 closest point's approximation) is presented in figure (6.17).

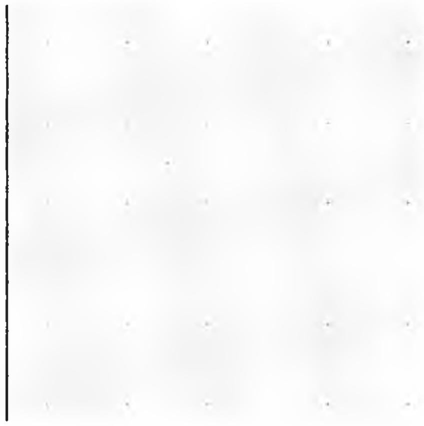


Figure (6.16) Measured Points in Virtual Field

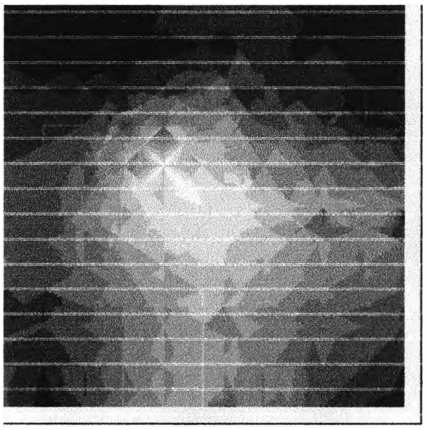


Figure (6.17) Represent 'Blanket' of Approximated Points Produced by Approximation Function '4 Closest Points'

The initial surface information presented on figure (6.7)

6.17.3 Achievement of required computational efficiency

Computational efficiency is important in practice. This concerns both the probability of the result and the time to deliver it. Bearing this in mind, the system cannot be allowed to iteratively calculate values to 1.10-7 accuracy when 1.10-2 is satisfactory. In the previous mathematical example it was decided to stop at the 10-th iteration to reduce the calculation time. Some artificial data become computationally expensive and it was decided to increase the computational efficiency to levels reasonable for the practice. Alternatively it is would be possible to dynamically control the precision of the model. In practise, if there were no other possibilities exist this would be a good option. Figure (6.17shows the output from the calculations, where the result, although not perfect due to approximations, definitely satisfies requirements.

6.18 Automatic Data Fusion and step by step user activity

6.18.1 Functionality

The main goal is now to resolve some of the challenges which were described in Part-1. The author consider this implementation to be a more elegant and precise expert system rather than a tool which only helps in the decision taking process and visual representation of the surface. A significant advantage of this system is that it uses expert database for weightings and thus does not rely so much on user experience. It is also platform independent, which means it can be installed on any operation system. It is several time faster then the Part1 software (which can be installed only in Microsoft operation system) and the approximation algorithm uses 4 points, instead of a maximum of 3. This gives a smother result in visualisation and the user has much more freedom in terms of options and views that make the decision making process easier. All functionalities cannot be compared just by examining the screens of the Part 1 and Part 2 experimental software. Most of these are explained in the following 'User Steps', in a similar manner as explained for the previous, Part I software application. The Part 2 application software is relatively more complicated and will thus require explanation in more steps. The application now consists of 8 panels rather than just 2 in the previous application.

6.18.2 User step 1: Loading the program and database

This system consists of two databases: one addressing the expert consideration of weight coefficients (reliability) for the different devices according to the different external data files and second with actual experimental data. This structure allows more precise decision making because of the expert recommendation for the weight coefficients. The 8 panels are: Load advice, edit file, Proposal, Load data, Statistic, Visualization, Abnormality, and Report. In addition, "help" button provide simple help for the system. When the system starts it always go to the first screen "Load advice" where the help field is located in the left side of the screen telling the user how the current step should be used. Standard boxes and fields for loading files are given in the first step and the user must locate the appropriate file with "exp" extension. This is done by double clicking on the file or by typing the name of the file and clicking "Open". A different view of the files in the local system also is provided, this presented in figure 6.18. All icons represent files or folders in the "My documents" folder on the local PC. IT should be noted that the user can also access files in any directory in the local machine or even on a remote machine (internet or intranet) and update the file "EXP" remotely. The "exp" file is a text file with complicated relationships. The structure of this file, which is not interested for the user, forms the expert file comprising rules and answers prepared by experts. They perform rule based approach to data (channels) evaluation. Here, the approach is to reduce uncertainty in the model mixture. This is realised by introducing weights (degree of believe) for every channel. Further to this, the degree of believe will be applied in the model mixture as the 'percent of involvement' of the channel. The system has a special parser which later visualise the information from this file for the user and finally extracts the weight for every used device. In this step, the user has to know how to locate the file and to load it into the system by pressing the "Open" button.

6.18.2.1 Load Advice Panel

Figure (6.18) illustrates the panel 'load advice' that allows the expert file (EXP) to be loaded. This panel consists of the standard Microsoft open file menu. Above the panel, an information line, which guides the user during the process of data evaluation, is created. Also on this panel is a small help box which explains briefly to the user the main functionality of the expert file system and the involvement of the rule base.

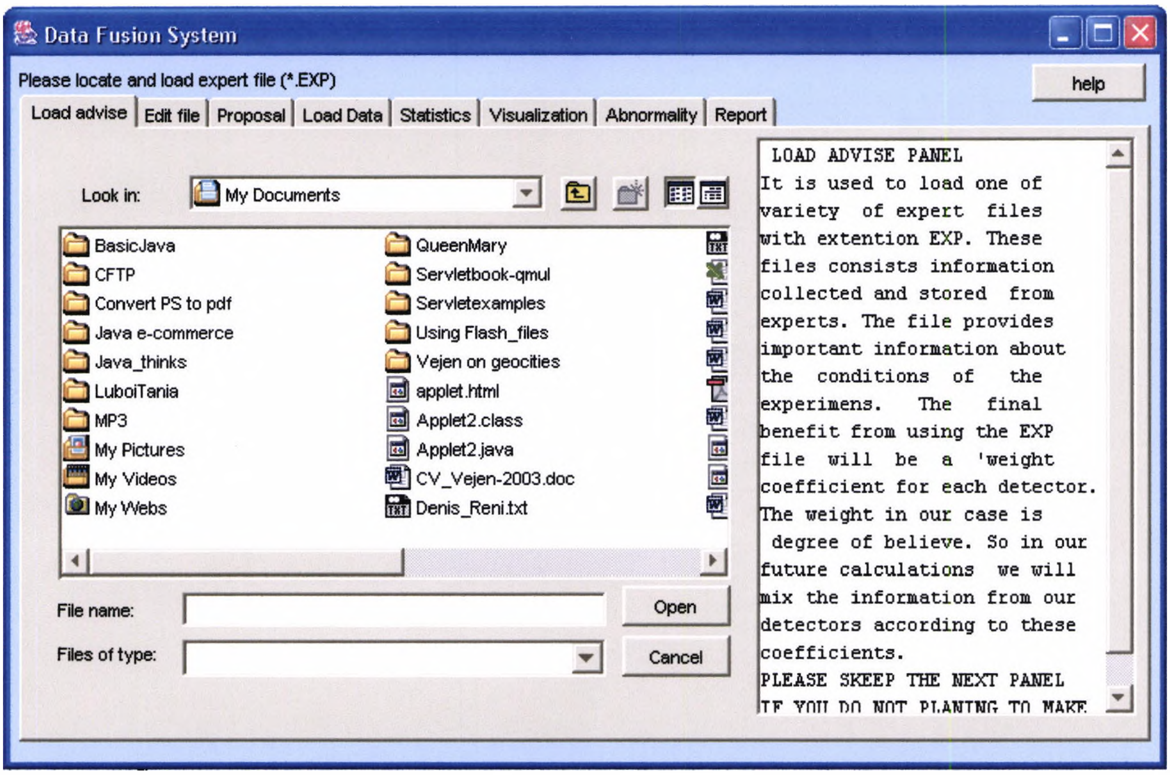


Figure (6.18) 'Load advice' Panel

6.18.2.2 Edit file Panel

The 'Edit file' panel comprises important information for experts. From this panel the user controls the operation of the rule base. In terms of functionality, this is a 'soft' approach, meaning that the rule base operation can be changed. This is advantageous for the system because users can operate with small, properly loaded files (EXP), , instead of loading a huge file by means of complicated software. An important point is that the author cannot include all possibilities (possible combinations and permutations for decision making process) in the EXP file. Furthermore, the user can rework files for specific options and also perform better data evaluation where necessary. Lots of variety can be demonstrated in terms of different rules and options. The freedom to reprogram this tool together with the possibility to use small files makes the system very flexible. At the same time it gives a good opportunity to initially reduced noise by proper use of the EXP file. All these possibilities for editing and saving the EXP file are included in the panel. A help panel provides information for the proper editing format.

A novice user is expected to use this panel as this requires expert knowledge. The information text at top of the panel reminds the user about this important step. The syntax for the expert file, which is described in the program, contains three levels of menu forms. It comprises several rules, an example of which is illustrated bellow:

- Line 1: buttons in the first row: button 1 button2...etc
- Line 2 comment which will be represented in the left screen
- Line 3 sub buttons in case the first button in the line 1 is pressed.
- Line 4 weights coefficients ordered according to the choice in line 3
- Line 5 sub buttons in case the second button in line 1 is selected
- Line 6 ....

The file follows the described structure until all conditions are represented. This structure allows construction of a complex, rule based, three level, fuzzy logic representation. This structure is important to the system because it describes conditions which are difficult to represent mathematically. Also, it includes logical rules accumulated as knowledge from experts. The mathematical representation of this knowledge is weight coefficients that represent degrees of belief.

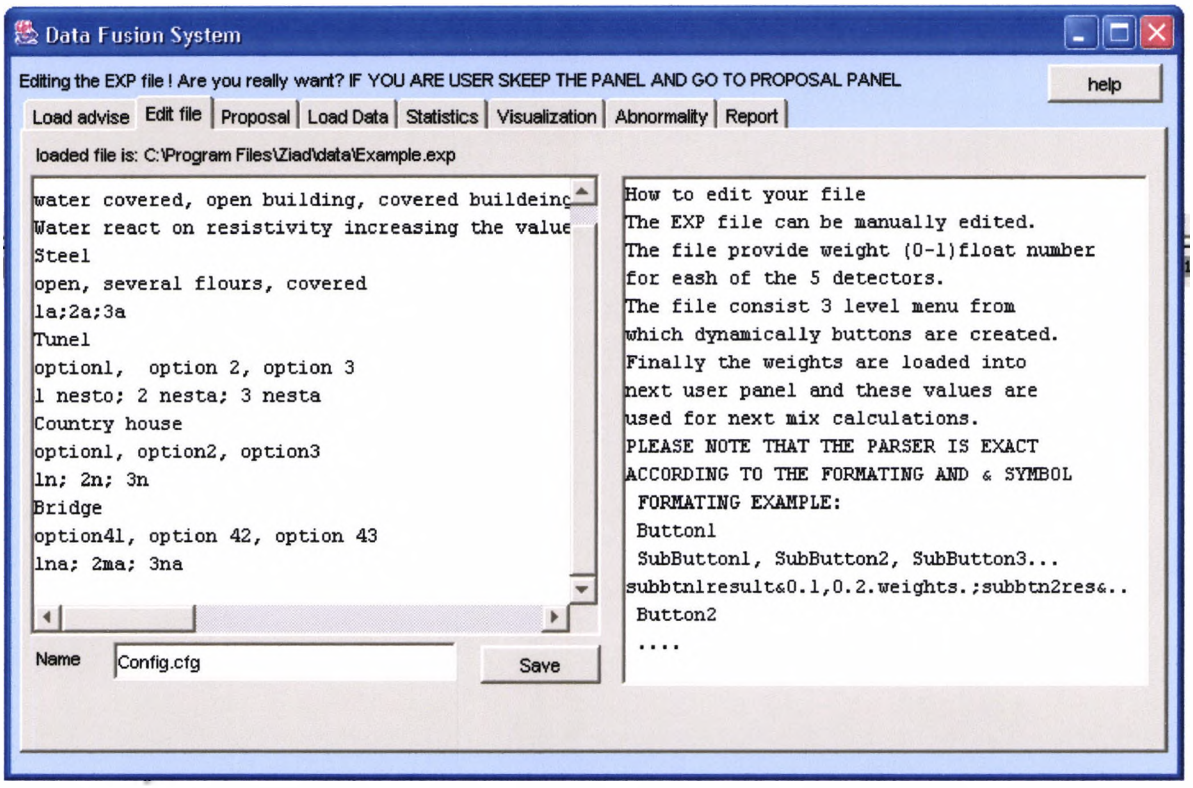


Figure (6.19) 'Edit file' Panel

6.18.3 User Step 2: Edit expert file

By clicking on the menu "Edit File" on top of the screen figure (6.19), the user loads the edit screen for the EXP file. Two fields appear on the screen where the expert user can edit the rules and conclusions for the (loaded) particular EXP file. All rules that create further dialogue with the user are presented in the right side of screen field. Using special notation, the expert can create different rules, change conditions and introduce different dependences in the weight coefficients. This convenient screen is designed especially for those who need to create, edit or test EXP files. The advantage of having this screen is to create a file that can be tested and used directly by the system. At the final stage, this file can be saved by entering the name in the "File name" field and pressing the Save button. This function creates possibilities for the reuse of old EXP files. By adding or modifying existing files the user can significantly reduce the amount of file processing in future runs of the fusion process.

6.18.3.1 Proposal Panel

The 'Proposal' panel presents the actual implementation of the rule based approach. Here the system reads the rule and parses through the structure of the EXP file to produce the appropriate screen buttons.

In an example case, there is a choice between water covered, open building and covered building. 'Water covered' is chosen in figure (6.20), which is fundamental for a bridge or concrete wall subject to the action of a river or sea. At the right side of the window there is important information relating to this particular case, explaining the weightings (The weights are shown after & symbol) chosen for each of the available NDT devices. For simplicity, the sum of all weighs is set as 1.0 and individual weights in the 0 and 1 range. This helps the author to introduce normalised probabilistic factors in the mixing approach.

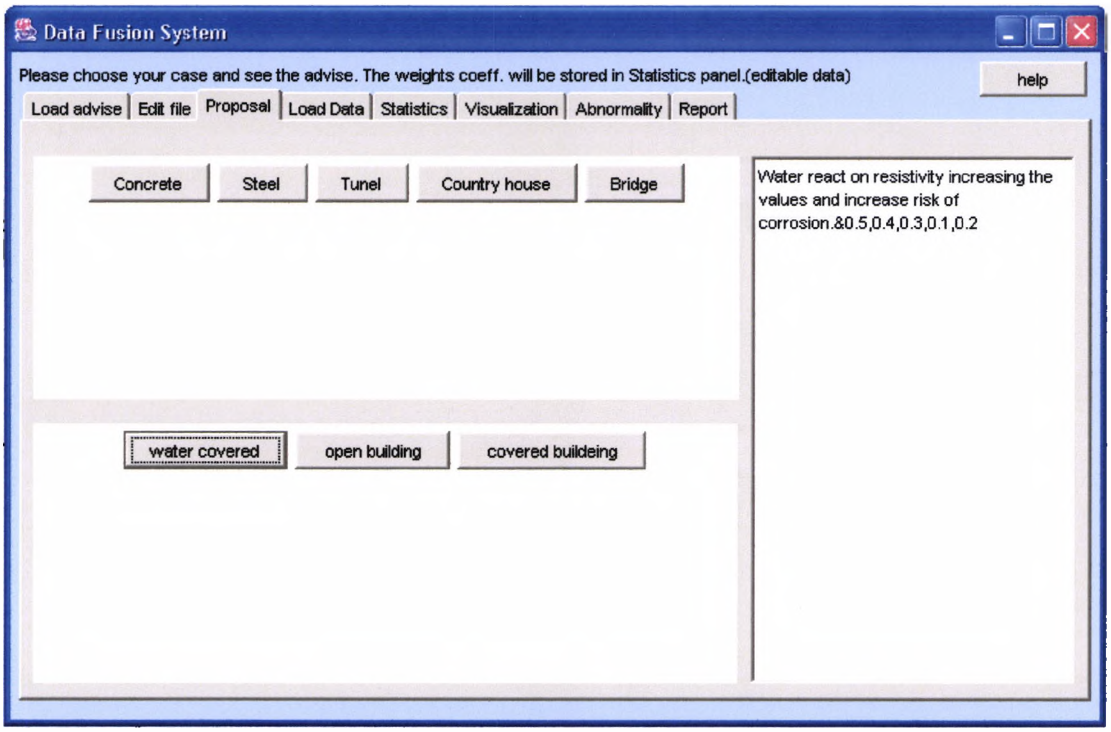


Figure (6.20) 'Proposal' Panel

6.18.4 User Step 3: Load Proposed Weight Data

To progress, the user has to press the appropriate button from the top row on the first field in the left side of the screen. In the example case: Concrete, Steel, Tunnel, are included in the options. These buttons are automatically generated by the system using the EXP file information. According to the user action (pressing one of these buttons on the first row), the system generates a second row (here represented as row in the bottom filed). From here, the system keeps requesting user selections until all conditions from the exp file are satisfied. Examining figure (6.20) it can bee seen that there are 5 initial conditions and, for the first option, there are 3 sub conditions which are:

- concrete construction water covered
- concrete construction on open
- concrete construction covered

To the right side of the screen the user can see the reason for the question prompt: resistivity measurements have different reliabilities or are actually impossible in some cases. This user action enables interaction between the expert file and the real data by introducing weight factors for every channel and device used in the current model mixture. After questions are answered, the expert file categorises the case and loads weight coefficients for every device into memory. Finally, the system jumps to the next option in the menu "Load data"

6.18.4.1 Load Data Panel

This panel is similar to the 'load advice' panel. Here, the user has to load the real measurement data file (.DAT file), which has format restrictions. The file must have measurements information stored only in the correct form.. Every row starts with values for x and y followed by the data (up to 48 measurements) separated by parentheses. One device (channel) it can have 100 measurements (points) and 48 measurements for each point. In total, the system can handle 24000 measurements. Important information for the system is the device data, which has to be in a separate row before the measurement data. The system recognises 5 channels names; Schmidt-Hammer, Covermeter(C), Covermeter(S), Half Cell, and Resistivity. The channels must be named with one of these names because the system matches them with internal variables. Only integer values are acceptable for measurement and coordinate (0-34565) data.

The information from the file is internally loaded in arrays. This reduces the input and output operations and accelerates the system. Also, as can be seen in the next panel. the system dynamically operates with the data that requires fast access. The input operation presents special parser which recognises the channel by the name and dynamically creates important information for the data which helps at a later stage to perform fast data editing and monitoring. When the user presses the button 'OPEN' the system automatically loads the next panel and starts calculating the global data.

6.18.5 User Step 4: Load data in the program

In this step the user has to locate the file with the experimental data values.. The fields are similar to step 1 except that the user loads another type of information. Pressing the "Load data" menu the user loads a file with extension "DAT". This file contains the measurement data obtained with different NDT devices. The actual transfer is performed for the selected file by pressing the "Open" button. A screenshot in figure (6.21) shows the file "testdata.dat" selected and ready to be transferred into the computer memory.

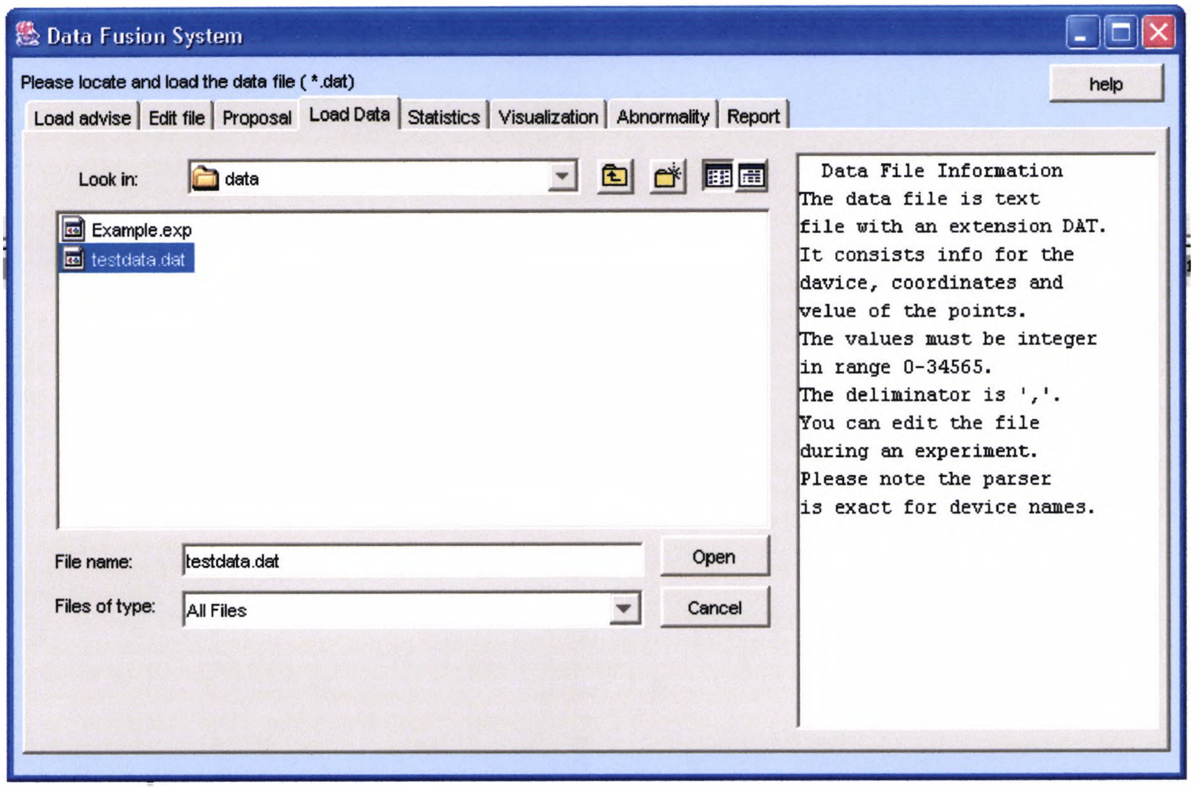


Figure (6.21) 'Load data' Panel

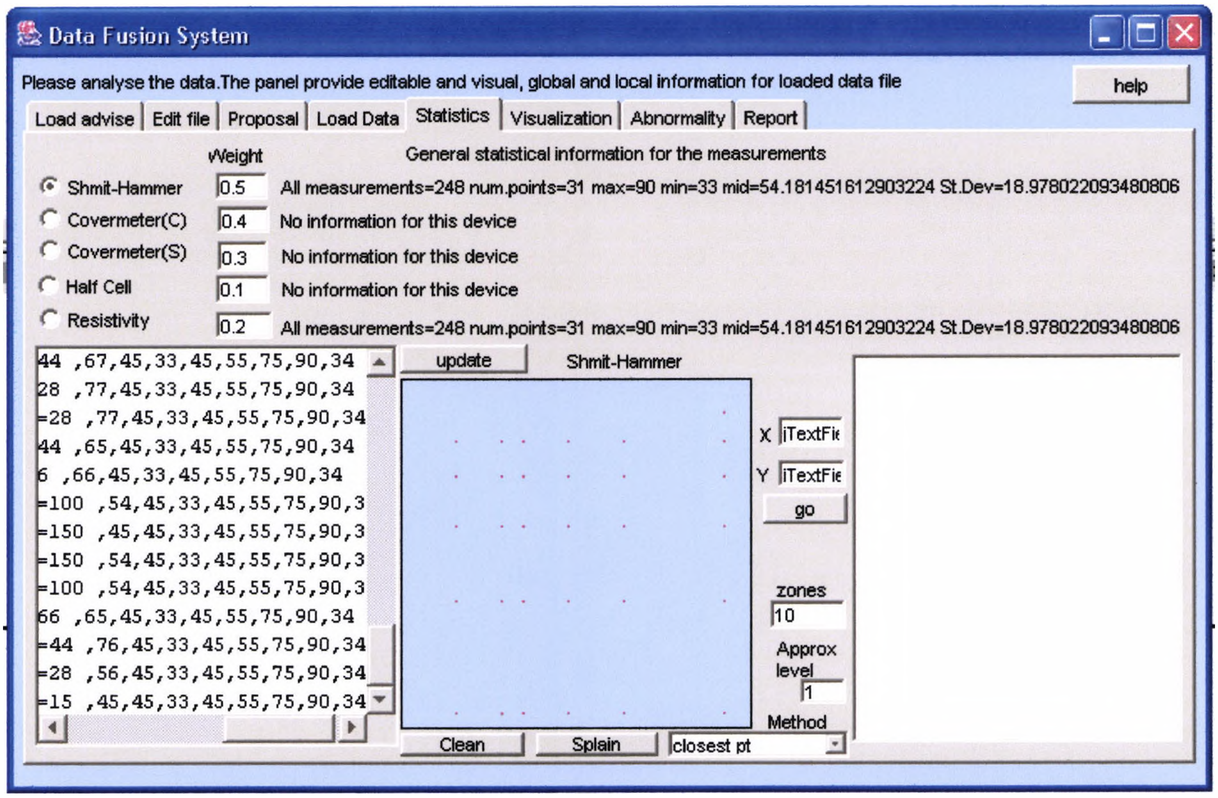


Figure (6.22) 'Statistics' Panel

6.18.5.1 Statistics Panel

This panel concentrates on the graphical and statistical methods of data evaluation. It is most computationally expensive due to the concentration of processing methods. The same fields express different information and can be used in different data evaluations. It is virtually divided into 4 zones:

6.18.5.1.1 Zone 1:

This is the top half of the screen. It presents the model's important global calculations which are starting before evaluation of local data. Basic information for every channel is shown in the following:

Number of all measurements: This quantity, which is needed for the estimation of statistical probability (must have more than 5 measurements), is derived thus:

$$M_{total} = \sum_{p=1}^{n}\sum_{m=1}^{q} measurement, \qquad 16$$

,where M_{total} is a number of total measurements for the channel, p the point in this channel to maximum value n, and m the measurement for each point to maximum value q,

The limits on the number of points for a channel are determined as:

Maximum value:

$$MaxV = Max(\sum_{p=1}^{n}\sum_{m=1}^{q} measurement), \qquad 17$$

Minimum value:

$$MinV = Min(\sum_{p=1}^{n}\sum_{m=1}^{q} measurement), \qquad 18$$

Middle value:

$$MidV = \frac{(\sum_{p=1}^{n}\sum_{m=1}^{q} measurement)}{n+q}, \qquad 19$$

And Standard Deviation:

$$SD = \sqrt{\frac{(\sum_{p=1}^{n}\sum_{m=1}^{q}(MidV - measurement))^2}{(n+q)-1}} \qquad 20$$

This zone also represents the weight for each channel extracted from this EXP file (rule based approach). Later, this information is important for the model mixture. At this stage the user has the possibility to change data values, which must be between 0-1 with 3 digits. The user has to always remember that the summation of these weight parameters must be (1.0). Five radio buttons are presented here, representing in same virtual panel data each of the data channels. Which channel is represented, depends on these radio buttons. Initially, the system marks the first of the radio buttons, which the user can change by simply clicking on an alternative.

6.18.5.1.2 Zone 2:

This is located on the bottom left corner of the panel. It shows all measurements and channels loaded from data files. Additionally, the system adds the number of measurements for each device and the number of measurement at each data collection point:

The Standard Deviation of the data for a particular point derived as:

$$SD_{point} = \sqrt{\frac{\sum_{m=1}^{q}(MidVpoint - measurement)^2}{q-1}} \qquad 21$$

This field can be edited, which means data can be delete, add or mixed with other data. This is important to combat the influence of false data that distorts the standard deviation value (as with the global measurement by a device). This is demonstrated using a simple example with imaginary data. We consider the case of a device having SD=0.5 with data for a measured point having SD=2. This would obviously attract the users attention towards checking the data, i.e. measurement as 20, 20, 20, 25432, 21, 20, 21, 20, 20... It is clear that the number 25432 is unreal and inconsistent with other channels. This then must be excluded to eliminate excessive noise at this point prior to data evaluation.

The system updates data every time the ‘update’ button is pressed. A special parser reloads the data which has been corrected and recalculated, including the global and local information. The user must input information in the format the system expects. The format is ‘string, x=value, y=value, measurement1, measurement2 etc. The system ignores the initial string, replacing it with new data (the number of the measurements by the device, number of the measurements for the particular point, standard deviation, coordinates x and y, with all data separated by a comma). When the user enter new values the ‘x=’ and ‘y=’ values are matched in the parser with internal strings enabling the system to load the data into the appropriate internal array. Using this mechanism, inclusion or exclusion of a single value measurement or complete rows of data is possible for a single point. Also, the channel’s name in the file can be changed. In conclusion, the enabled user interaction with data files gives them a powerful mechanism for noise reduction. As far as practical, the systems ensure interactions are performing correctly.

6.18.5.1.3 Zone 3:

This zone is located in the middle panel of the graphical output screen. At this stage, there are different options to control the view, with one channel at a time graphically presented. The graphical output presented is only for the Schmidt-Hammer data channel. To switch between channels, the user must select the appropriate radio button in Zone 1. The working channel identifier appears at the top of the graphical output. This tool performs several operations, by which it is possible to have eight different data presentations in the graphical output:

6.18.5.1.4 Dot Representation

This is default situation for the screen, as shown in figure (6.14). The dots (red) represent the measured data for the selected device channel. The surface is scaled according to the extreme points in all the available channels. The location of every measurement point for each channel is displayed by selecting appropriate radio button in Zone 1. By pressing the ‘clean’ button the user can return to the Dot presentation and then view other data as required. Operating the clean command returns the view illustrated in figure (6.23).

Figure (6.23) Dot Presentation in Graphical Output

6.18.5.1.5 Spline using closest point

This is an approximate graphical presentation for every point on the surface. The main rule for the approximation is:" The point value will be the same as the value of the closest point from the database". The presentation is crude but adequate for some experiments. An example is presented in figure (6.24), for demonstration purposes only.

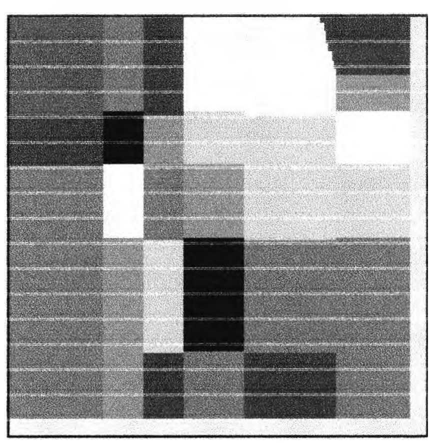


Figure (6.24) Spline Using Closest Existing Point Value

To produce this figure the user simply has to locate the 'closest point' from the drop-down menu and to press the 'Spline' button in order to make a choice.

6.18.5.1.6 Spline using 2 closest points:

This can be produced by selecting the '2' located in the centre of the drop down menu. The mathematical equation which describes this method is:

$$V_{x,y} = \frac{V_{x1,y1}(closest1) + V_{x2,y2}(closest2)}{2} \qquad 22$$

Where the closest point to the point required means another point that is available in the database provided. The result is presented in figure (6.25).

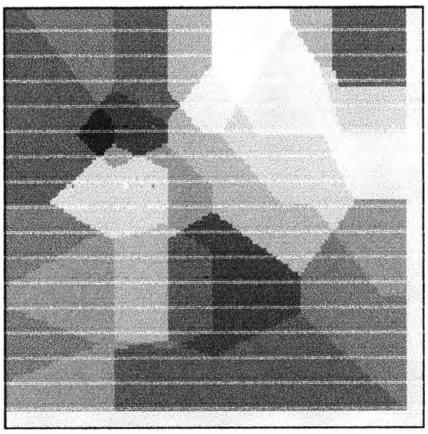


Figure (6.25) Closest 2 Point Middle Value

6.18.5.1.7 Spline using 3 closest points:

This is similar to the previous case, except for choosing a different option from the drop-down menu and invoking a different mathematical model. The result is presented in figure (6.26).

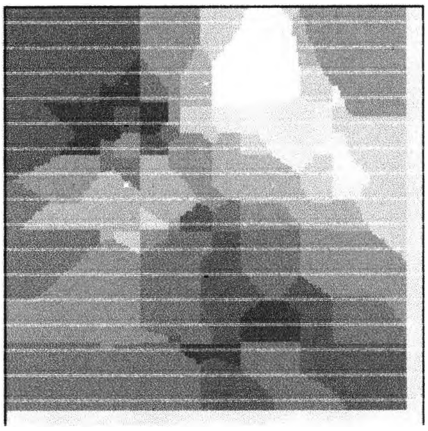


Figure (6.26) Closest 3 Point Middle Value Approximation

The Spline using 4 closest points is presented in figure (6.27).

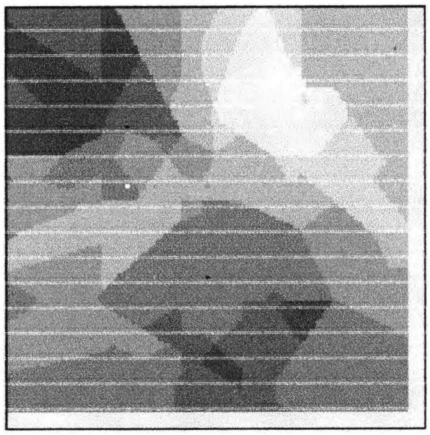


Figure (6.27) Closest 4 Point Middle Value Approximation

6.18.5.1.8 Approximation using 2 closest points:

This method explores the mathematical evaluation of the distance between two closest points with existing values, to approximate the value for required point. The result is shown in figure (6.28)

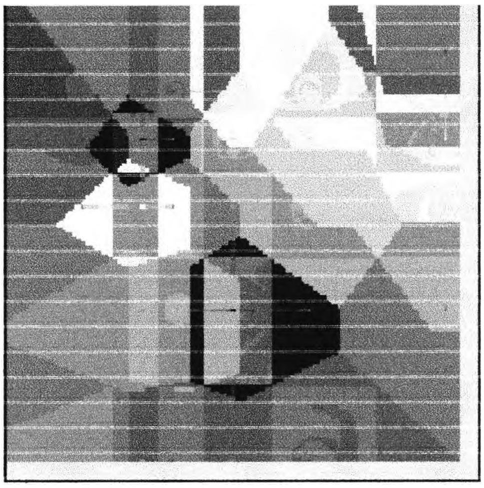


Figure (6.28) Distance-Value Approximation Using 2 Closest Points

The approximation using 3 closest points is presented in figure (6.29).

Figure (6.29) Distance-Value Approximation Using 3 Closest Points

The approximation using 4 closest points is presented in figure (6.30).

Figure (6.30) Distance-Value Approximation Using 4 Closest Points

6.18.5.1.9 Control of presentation depth

This means that the user can control as many zones as required in the output. In some cases, three zones scene segmentation may be satisfactory. In some special cases the requirements may be more. This can be controlled by changing the value in field named 'Zone'. By default, there are 10 zones, giving acceptable scene segmentation. Bellow is a presentation of the same view with 2 difference scene segmentation depths. The difference can be exploited by the user, although in some cases simple segmentation is all that is required. Also, by changing the depth, the user can view detail differences which are otherwise hidden if only one depth were initially chosen.

Figure (6.31) 4 Points Approximation Method with Depth = 50

Figure (6.32) 4 Points Approximation Method with Depth = 10

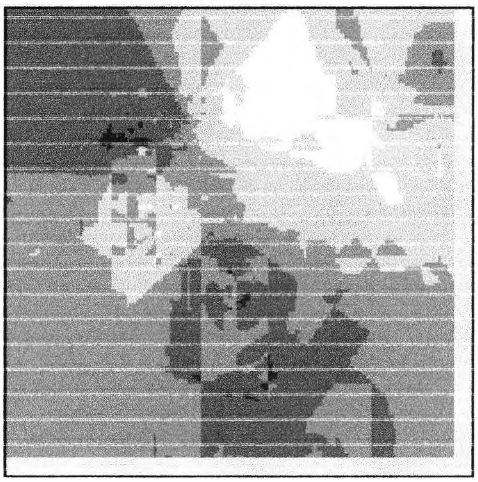


Figure (6.33) 4 Points Approximation Method with Depth = 5

6.18.5.1.10 Approximation level

There is a further mechanism to control the visual presentation. For the last 3 functions in the drop-down menu, the user can control the iteration threshold level. This means that the user can exit from the interactive loop before the algorithm (mentioned earlier) is completed to merge virtual point values. The algorithm will be approximate if the difference between calculated points is less than the threshold. The system will then perform calculations according to a simple mean function, using the approximated virtual data from the iteration engine. This tool is important because it allows precise control of the accuracy of results and the calculation time. By default, the control value is 1.0.

6.18.5.1.11 Zone 4

Strictly speaking, Zone 4 uses the view from zone 3 together with the output field displayed on the 'Statistic' panel at the bottom right corner. Because the Zones are divided according to function, this zone is called the output zone. This is where the results of users actions are monitored. This zone concentrates on single point monitoring and evaluation, rather than a global view of the data. If a view is chosen in Zone 3, two methods of calculation can be activated for a particular point:

- By simply clicking with the mouse over a location in the graphical view,
- By precisely entering its x-y coordinates (in special fields located right of the graphical panel) and pressing the 'Go' button.

In both cases the system outputs data for the monitored point. At this stage, there are two choices. The chosen point can be a point from the database, in which case the system outputs just the value or, the point is approximated using a method selected from the drop down menu. As an example, in the case of the ' 4 point approximation method', Schmidt-Hammer channel values at coordinates X=120 & Y=27, are output as shown bellow:

==

Schmidt-Hammer point: X=120 Y=27

The 4 closest points are:

Point 1 X=100 Y=28

MaxVal=90 MinVal=33

Mean=56.75

Distance=20.024984394500787

Zone 1 (33.0-44.4) =25.0%

Zone 2 (44.4-55.8) =37.5%

Zone 3 (55.8-67.2) =0.0%

Zone 4 (67.2-78.6) =25.0%

Zone 5 (78.6-90.0) =12.5%

Point 2 X=145 Y=28

MaxVal=90 MinVal=33

Mean=54.125

Distance=25.019992006393608

Zone 1 (33.0-44.4) =25.0%

Zone 2 (44.4-55.8) =37.5%

Zone 3 (55.8-67.2) =12.5%

Zone 4 (67.2-78.6) =12.5%

Zone 5 (78.6-90.0) =12.5%

Point 3 X=100 Y=44

MaxVal=90 MinVal=33

Mean=55.25

Distance=26.248809496813376

Zone 1 (33.0-44.4) =25.0%

Zone 2 (44.4-55.8) =37.5%

Zone 3 (55.8-67.2) =12.5%

Zone 4 (67.2-78.6) =12.5%

Zone 5 (78.6-90.0) =12.5%

Point 4 X=145 Y=15

MaxVal=90 MinVal=33

Mean=52.75

Distance=27.730849247724095

Zone 1 (33.0-44.4) =25.0%

Zone 2 (44.4-55.8) =50.0%

Zone 3 (55.8-67.2) =0.0%

Zone 4 (67.2-78.6) =12.5%

Zone 5 (78.6-90.0) =12.5%

==

Approx. value is: 55.20254235487363

The system outputs (for each of the four points) several important values including max value, min value, mean value, distance to the points, and distribution (the distribution is performed in 5 bins with the output measured as the percentage for the bin). A normal distribution is expected for the data; otherwise these measurements (points) cannot be relied on. The final approximation result and the corresponding point coordinates are shown in the display. All this information can be used to evaluate the reliability of results.

6.18.6 User Step 5: Performing statistical analyses

As previously mentioned, system representation is dynamic, which means that every user activity in the fields with values triggers recalculation of all information displayed on the screen. Having an environment several times faster than that of Stage 1, this process is almost instantaneous (the Stage 1 mathematical model took about 2 minutes to progress the graphical representation). Here, user activity is based on interactions for noise reduction rather than following set procedures. This process might require several steps and editing of the initial data. By way of an example, typical user activity is described in the following.

First user action is to monitor the global statistical representation of the data shown at the top of the screen. This information, (calculated using equations 16, 17, 18, 19) represents the global data representation for each device. Weighting coefficients are transferred automatically from the expert file and the user can go back to the initial data and edit it. This would be relevant in cases of very high standard deviation or data with a very large difference between maximum and minimum values. Also, the user can edit the default weighting parameters. They can be adjusted according to the statistical performance of the device involved in the measurement. After receiving satisfactory data representation for the statistical calculations the user can view the graphical representation of the surface. As in the Part 1 application, the user can observe approximation to any point on the surface by clicking in the required locality on the graphical screen. Also, the representation of the surface can be seen by clicking the "Spline" button. This time the user has possibilities to chose from 7 different approximation models together with a level of result representation. The graphical output corresponding to the different options is correspondingly presented in figures (6.24), (6.25), (6.26), (6.27), (6.28), (6.29), (6.30), (6.31), (6.32), and (6.33). All these functions allow users to view the different features of the surface. The total range of views is 7 models * 255 grades (zones) * 255 (maximum approximation level values) i.e. 455175 view combinations. All control boxes are located on the left side of the screen. In this example the single closest point ("the closest point") approximation method used with 10 zones of the surface representation. These 10 zones are shown as 10 grades of the graphical field. The term 'Approximation level' refers to the mathematical precision that the algorithm provides. This part of the program uses equations 22 and all the equations referred to I the previous "Algorithm's challenges" section i.e. equations 8, 10, 11, 12, and 13. All equations use parameters collected from the input fields as "zones", "approx. level" and "method". Here, is not possible to represent the program in a linear way because the system is action driven rather than a "to do"list. User actions effect the presentation of this screen, which means that if the user changes even one value, all data displayed on the screen is recalculated.

6.18.6.1 Visualization Panel

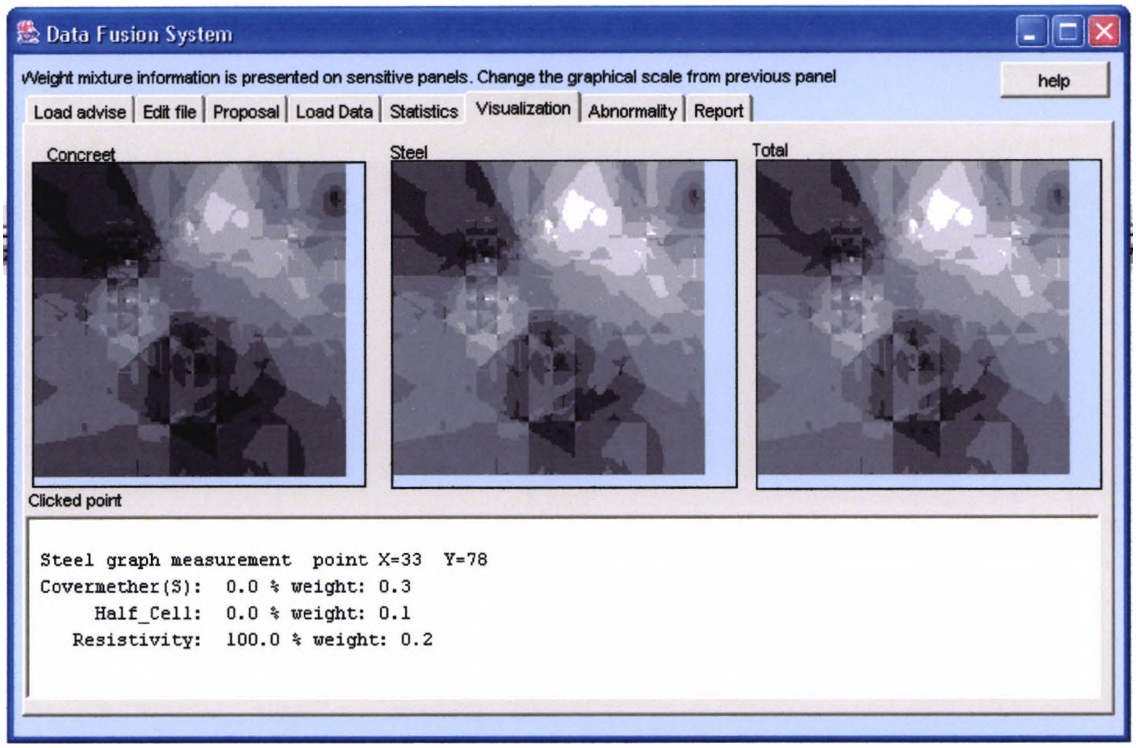


Figure (6.34) Panel 'Visualization'

The 'Visualization' panel performs model mixing, with graphical output that reuses the graphical parameters set in the 'Statistics' panel. The three graphs represent the complete information for 'Concrete', 'Steel' and their Combination. According to this mapping, the weakest place is shown dark and the strongest white. The calculation for 'Concrete' involves only the first two channels, the calculation for the 'Steel' three channels and 'Total' all channels. The calculation for 'Total' is performed according to the formula:

$$p_0(x,y) = \frac{\sum_{ch=1}^{n} K_{ch} \frac{p_{ch}(x,y)}{\max p_{ch}(x,y)}}{n} * coef_{os}, \qquad 23$$

Where po(x,y) is the output point x,y, Kch the weight coefficient for each channel, n the number of channels, maxpch(x,y) the maximum value for data on a particular channel and coefs the output scaling coefficient. According to this equation, the output is normalized and, therefore, no longer consists of real values. From this point onwards, the evaluation at a particular point or location only as reliable as the neighbouring data.

Obtaining the result, which shows the weight and percent of involvement of each channel, is done by clicking one of the panels. If some unreliable data is found, the user can return to the 'Statistics' window and perform evaluation of real data rather than virtual (after model mixing).

The disadvantage of the mixed model approach is the lose of connection between real values. On examining at the graph, it is difficult to determine what is wrong. This is due to the virtual data environment that lacks the possibility of pin-pointing errors. The advantage is that users can easily evaluate data visually and thus reduce noise by combining several information channels.

6.18.7 User Step 6: Visualisation

This screen is activated by pressing selecting "Visualization" from the system menu. The user has the possibility of producing and monitoring data for different points, by clicking at the chosen location on the graph. All information for this point is displayed in the text field. At this stage in the program execution, defects arising in the concrete or steel can be clearly distinguished.

The mixed model performs three steps to produce the final total graph. Firstly, equation 23 is applied to all reinforcement sensor data, and then to channels for concrete parameter data. This graph is presented under the name "Concrete", with "Total" finally produced by the same equation. At this stage, the user can return to the previous menu and follow problems by selecting "Abnormality".

6.18.7.1 Abnormality Panel

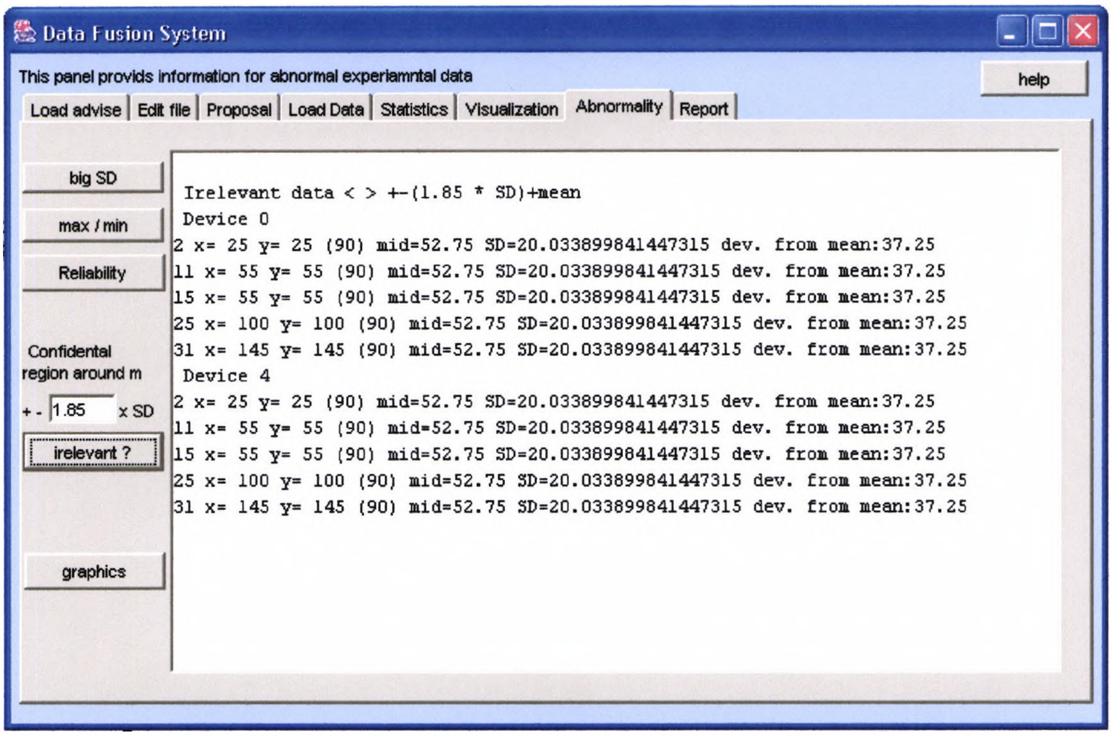


Figure (6.35) 'Abnormality' Panel

The 'abnormality' panel is provided to make numerical data evaluation more straightforward. According to set rules, data may be considered to be abnormal. There are five options for data evaluation giving local and global results. These methods are:

- Large SD: The greatest standard deviation can be shown with the standard deviation for each channel.
- Max/min: This function calculates the maximum and minimum values for every point's measurements on each channel. The "reliability" provision shows the weight used for every channel.
- Irrelevant data around SD: This method calculates and presents all points out of the 'confident region' around the mean of the data. The user can generally control the confidence region by introducing a special coefficient K, the confidence region calculated as:

$$Conf\_reg = \mu \pm (SD * K) \qquad (24)$$

, where K: is the user controllable coefficient. The result is output to the text field, which can be changed by the user.

6.18.8 User Step 7: Abnormal values

All screens that include "Statistics" calculate global statistics parameters with the possibility for manipulating values or re-designing the classification conditions. The menu includes five especially designed global functions based on all data rather than single point measurements. These functions are designed to highlight irrelevant data i.e. all data lying outside the confidence region as opposed to data lying with the minimum or maximum values of all samples. The user can undertake measurements in order to clarify or re-evaluate previous parameters such as weight, view parameters etc. A list of all abnormal points is printed after the activation of any function. For example, in figure (6.35) all points are presented outside the 1.85 * standard deviation boundary. The user can decide to include or exclude these points in the mixture.

6.18.8.1 Report Panel

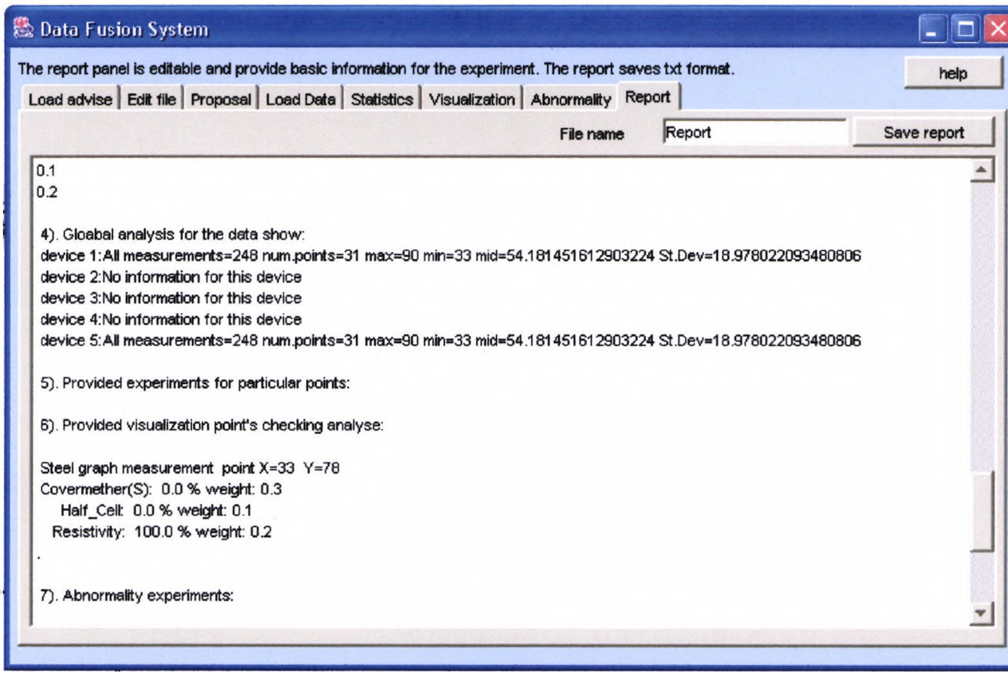


Figure (6.36) 'Report' Panel

The 'report' panel consists of three components: 'Save', 'Name' and 'Report'. The panel automatically collects all information from all previous panels, sorts it internally and outputs the data and conclusions from previous experiments. Ready for manual editing, the 'Report' panel gives an easy means of collecting results and creating a report on measurements. The result can be also copied and pasted into a word document file or other program.

6.18.9 User Step 8: Collection of Report data

By pressing the "Report" button the user changes the screen view. Here two main components are important, the 'Edit' field which is the largest field on the screen and "File name" field together with the button "Save". A special automatic "collection agent" (software sub-program) collects all information and test data from previous screens and pastes it here.

The report is created with information ordered according to several main points. For example, in figure (6.36) a report is presented with paragraphs 4, 5, 6 and 7 visible. For presentation purposes, the system tries to organise the editable report by introducing numeration. To help with reporting, the user can also paste, delete, copy or change everything on the screen. Finally, a report can be saved as a text file using the "Filename" field and "Save" button

The structure of the generated report file is as following:

1. The name of expert file used with answers generated
2. The weights used
3. The global analyses data
4. All data point results from experiments
5. All point data tested during visualization processes
6. All data from experiments with abnormalities

The following part of the program is responsible for this data collection process:

```
jTextPane2.setText("          R E P O R T "+
"\n\n 1). The initial expert file is "+jFileChooser1.getSelectedFile()+"."+
"\n From the proposal options the expert result string is:"+ jTextPane1.getText()+"."+
"\n\n 2). The data file with name "+ jFileChooser2.getSelectedFile()+" was loaded."+
"\n The working data are:\n"+jTextArea3.getText()+"."+
"\n\n 3). The weights for the devices are:"+
"\n"+jTextField2.getText()+
"\n"+jTextField3.getText()+
"\n"+jTextField4.getText()+
"\n"+jTextField5.getText()+
"\n"+jTextField6.getText()+
"\n\n 4). Gloabal analysis for the data show:"+
"\n device 1:"+jLabel3.getText()+
```

"\n device 2:"+jLabel5.getText()+

"\n device 3:"+jLabel6.getText()+

"\n device 4:"+jLabel7.getText()+

"\n device 5:"+jLabel8.getText()+

"\n\n 5). Provided experiments for particular points:"+ jTextArea4.getText()+

"\n\n 6). Provided visualization point's checking analyse:"+

"\n"+jTextArea5.getText()+"."+

"\n\n 7). Abnormality experiments:"+

"\n"+jTextArea6.getText()

The final conclusion will be only a paragraph which is added manually into the report to complete the measurement.

6.18.9.1 Help Button

This button, which is designed for quick help (top right corner), displays a small window with help information and all instructions to the user. It explains functionality and operational possibilities with the system. Figure (6.37) gives a view on the help window.

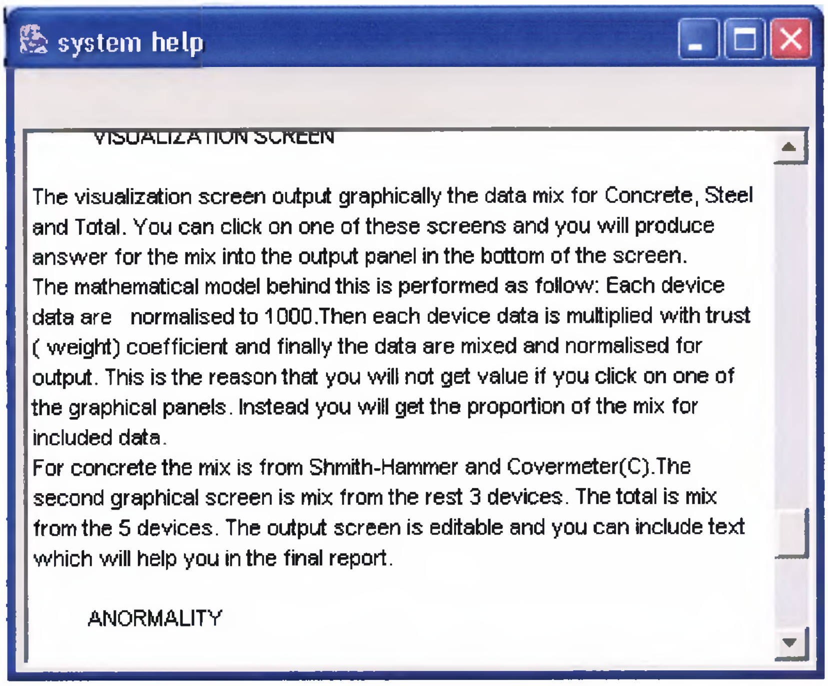


Figure (6.37) 'Help' Panel

6.19 Tests with artificial and real data

6.19.1 Tests with artificial data.

Testing with artificial data is an important stage. Using this approach, it is possible to test the system stability in extreme conditions by creating unreal data and exploring the possibility of interrupting or misleading algorithms. Whilst the system is not protected from user errors, the users can undertake experiments to test the stability of the mathematical model. The author has created and experimented with several sets of artificial data to confirm the reasonable robustness of the software.

In these designed evaluation files, data was omitted, and high level of noise and incorrect distributions introduced. The system proved to be stabile, tracked and removed noise in the GUI (low and mixed level) and reduced calculation time. Also, the possibilities for improving the quality of the conclusion are successfully monitored. Missing data did not disturb calculations. Overall and the system delivers a 'user friendly' GUI convenient for effective human-machine interaction.

6.19.2 Tests with real data

Experiments with different real data were undertaken. A comparison with conventional calculations and data evaluation was made. Compared with the results from the Part 1 approach, the system benefits from better data representation and conclusion quality. Processing time reductions have been achieved and data storage and transmission improved.

6.19.2.1 Stability

The author undertook stability tests and compared the results with the conventional standard manual method of data evaluation. The artificial data was created with varying signal noise (different data distribution, different standard deviation, missing data and randomly speeded points into the surface). In all cases the system showed better results, comparable to evaluating data using only one channel or manual evaluation of separate channels. The following table (6.2) evaluates how well this system performs

As a demonstration tool, the system is not protected from erroneous user input in terms of syntax errors. The industrial system should cover this problem by simply handling the input by a special parser. Also, system communication (input/output) at present time is organised as text file. An industrial system would require more stability, implemented as a XML document with high re-usability. The system could be a server application instead of standalone. All these changes would improve system stability, making it superior from a technical point of view.

Factor	DATA FUSION	STANDARD
Time taken to reduced noise in a set of measurements	10-15 min	45-55 min
Probability of the result	Rely of the human supported by mathematical calculations	Rely only of the human
Possibilities for storing and transmitting data	Yes	Difficult
Data visualization	It is possible to visualise all channels separately in 8 different methods plus the mix components ie. for Steel, Concrete or Total	Very time consuming process. Manually the 'dots presentation' is possible. The rest of the methods require computational power.
Possibility for forward/backward analysis	Yes	Can only process forward
Flexibility with mixed model	5 channels can be included into the mixture	Needs complex calculation even for a combination of 2 channels.
User expertise & experience required	User should understand the process and be able to operate the man-machine interface. They have the chance to rely on expert opinion in the system's mathematical conclusions .	For the same quality of the result the user should have extensive knowledge of concrete deterioration & repairing and be able to evaluate computationally tedious statistical data.
Final conclusion creation	The system keeps track of every experiment and pastes these into the final editable field. All data can be edited and copied and pasted as textural information	The user must create all report documents from scratch.
Knowledge reusability	The system has a rule based knowledge system with high data reusability. Several expert files can be created, which the system . can reuse.. Additionally, visual information and conclusions resulting from internal calculations can be monitored, saved and reused in future data evaluation.	Small knowledge reusability. The system relies on current user experience and knowledge.

Table (6.2) Comparisons of Methods

6.20 Experiments

The following describes is a real life example where the programme is used to fuse two sets of NDT methods data collected from an open concrete structure (Car Park). The two NDT methods providing data are Schmidt-Hammer and Covermeter. Unlike the Stage 1 programme, the Stage 2 does not need an comprehensive Excel input file, only a simple text file is required. Gathered data is presented as follows:

Schmidt-Hammer

0,0,35,33,34,31,37,31,31,39

400,0,33,40,39,38,40,34,34,39

800,0,36,35,38,41,33,44,44,41

1200,0,40,36,40,34,31,32,34,29

0,300,30,32,30,33,34,33,30,30

400,300,39,35,40,34,35,37,42,37

800,300,46,43,39,42,41,42,42,40

1200,300,31,39,36,32,39,37,35,34

0,600,41,42,36,38,38,38,39,34

400,600,35,31,35,32,35,33,36,38

800,600,32,37,33,33,36,35,39,37

1200,600,35,37,34,36,33,32,35,29

0,900,33,29,28.8,25.1,30.6,28.9,30.4,28.4

400,900,22,25,24,22,29,27,26,22

800,900,30,31,35,30,39,38,32,33

1200,900,23,24,23,29,25,28,23,30

0,1200,21,20,26,21,22,25,26,21

400,1200,16,23,17,23,22,17,17,21

800,1200,30,25,25,25,22,22,27,24

1200,1200,28,22,22,22,30,27,22,29

Covermeter(C)

100,100,48,52,62,64,63,63,53

200,200,46,50,60,61,63,63,52

300,300,46,45,58,58,63,63,46

400,400,40,40,58,58,63,63,42

500,500,38,39,56,58,63,63,40

600,600,37,38,54,56,62,62,38

700,700,36,36,53,56,62,62,36

800,800,35,34,50,56,62,62,35

900,900,30,33,50,54,62,62,35

1000,1000,30,33,50,54,62,62,35

1100,1100,25,30,49,54,61,61,34

1200,1200,20,25,49,52

As can be seen above, the data is presented in a very simple way, as a "dat" file.

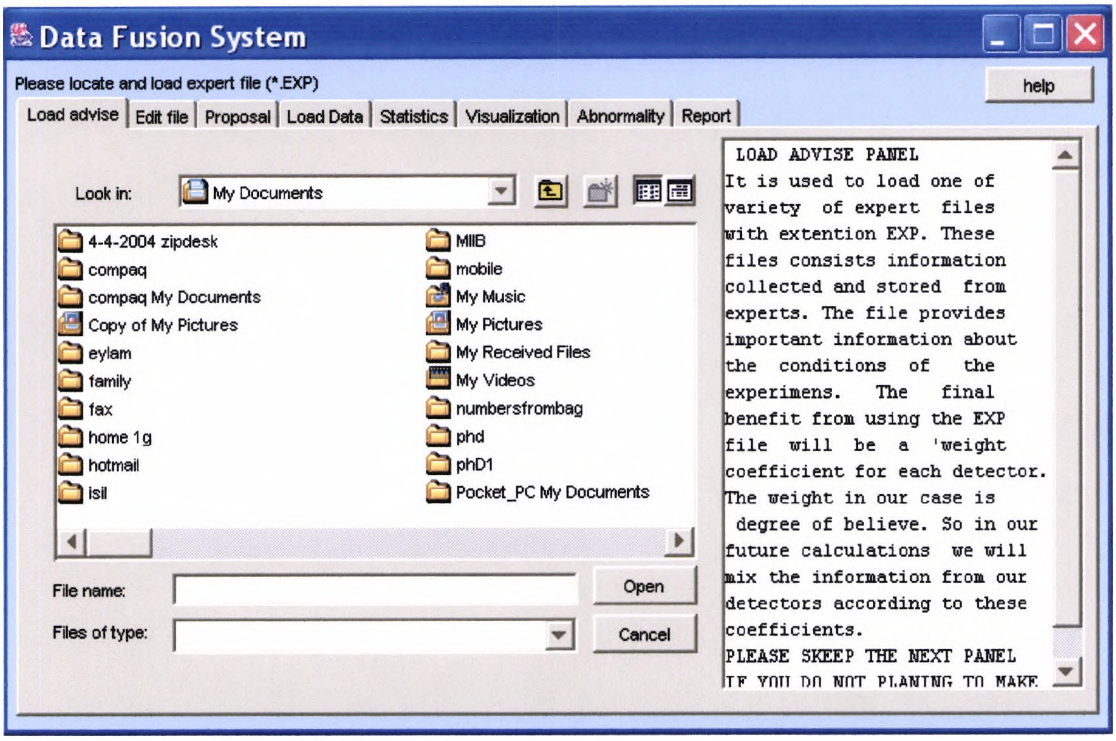


Figure (6.38) Screen 1

The example file, which is can be modified by the user, has been loaded in the system as illustrated in figure (6.38). Several options are displayed. Clicking "Edit file" displays a text that explains how to edit the file.

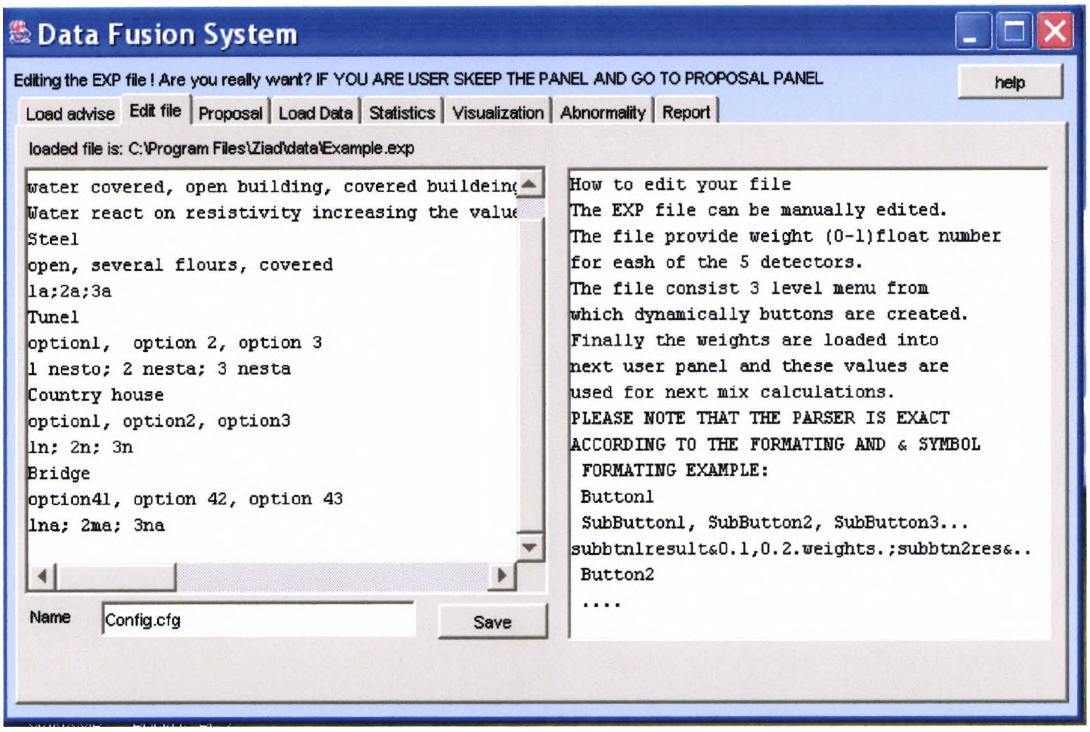


Figure (6.39) Screen 2

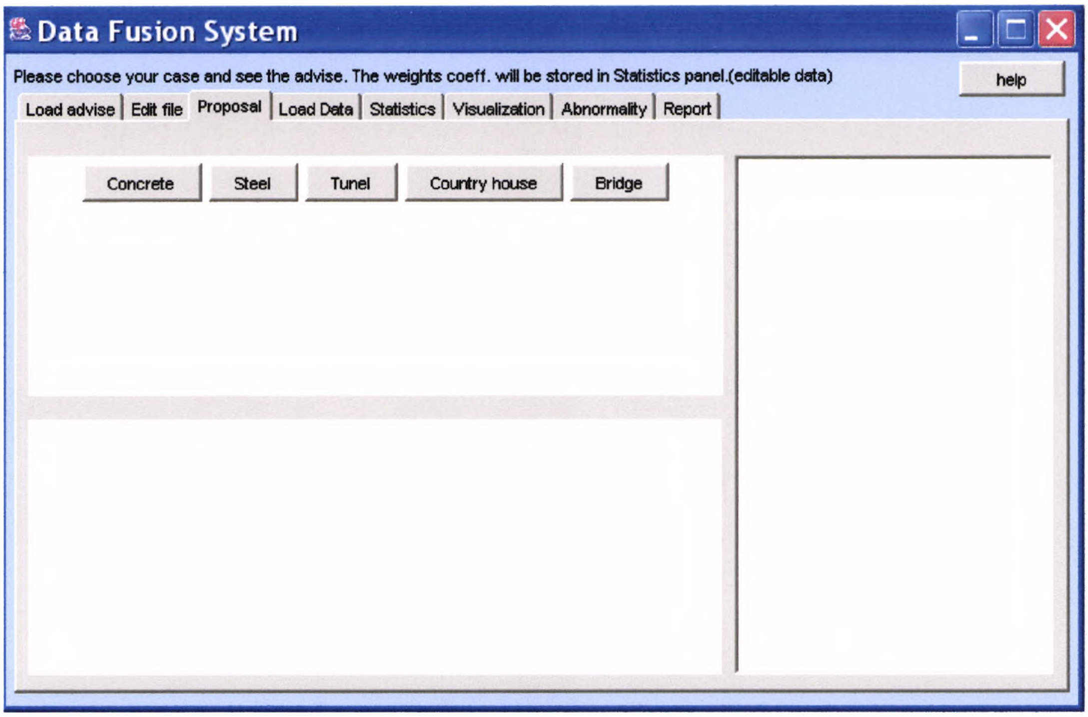


Figure (6.40) Screen 3

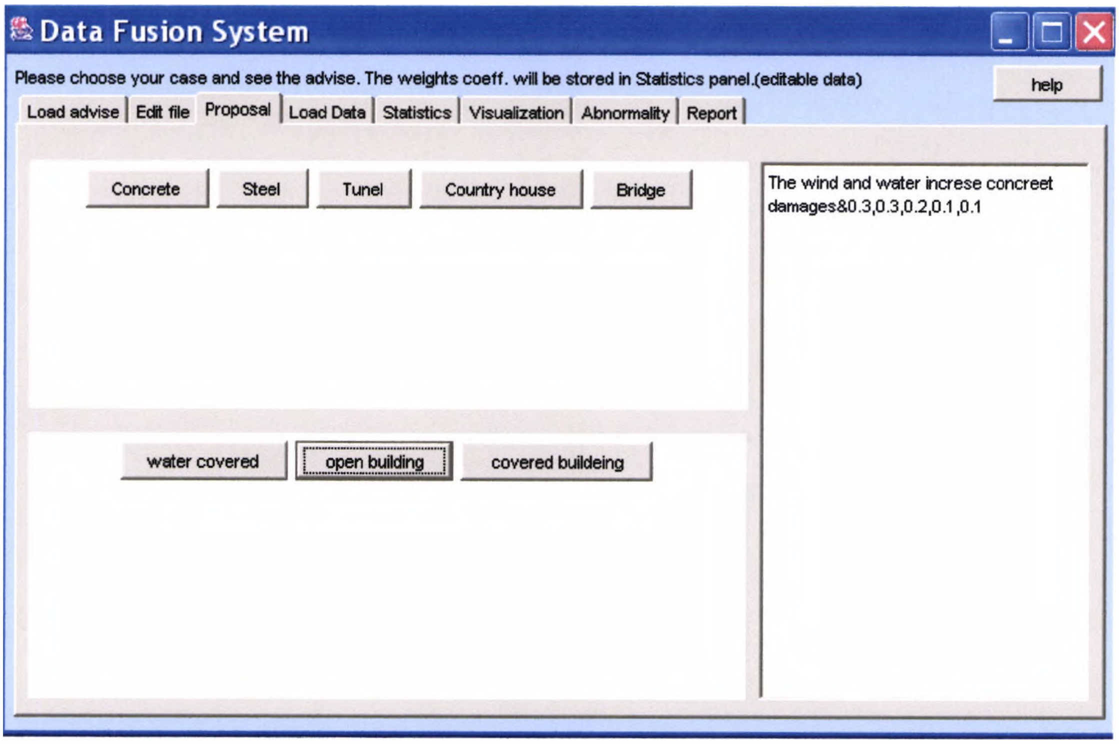


Figure (6.41) Screen 4

On selecting "Proposal", options and advice appears on the screen as illustrated in figure (6.40). Use of the options provided is illustrated in figure (6.41), where concrete structure was chosen. Three options were made available, the user selecting a car park as an open concrete building. Default weighting ratios are given on the same screen that can be optionally modified during execution of the programme.

The collected NDT data is loaded on activating the "Load Data" button and saved ready to be inputted in the system. In figure (6.42) it can be seen that only two NDT methods were used, therefore, the weight advised by the programme cannot be used because the other three results are not available, an instance of the programme advising that it will not accept data for various reasons (e.g. spelling mistakes and incompleteness). Also, on this screen, the user can examine data at any location in the inspected area, simply by clicking within the rectangular shape representing the concrete slab. It is important to mention that not all the displayed data is NDT data; most of it being calculated by one of statistics methods previously explained in this chapter.

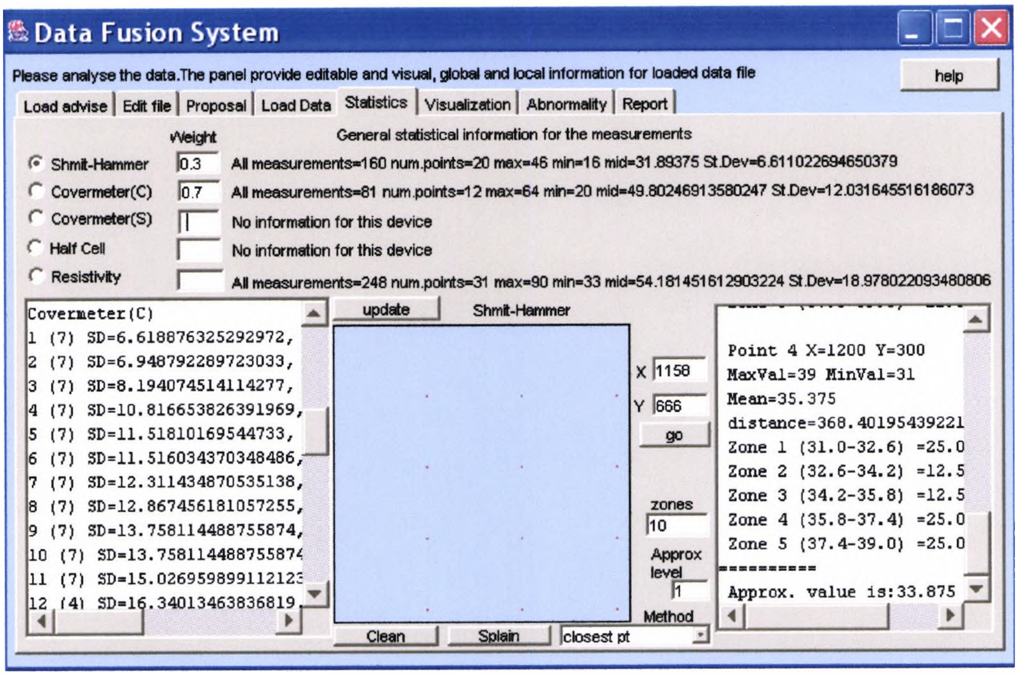


Figure (6.42) Screen 5

Figure (6.43) illustrates how the fused data is graphically presented, the area provided on the bottom of the screen being allocated to the output of specific data required by the user.

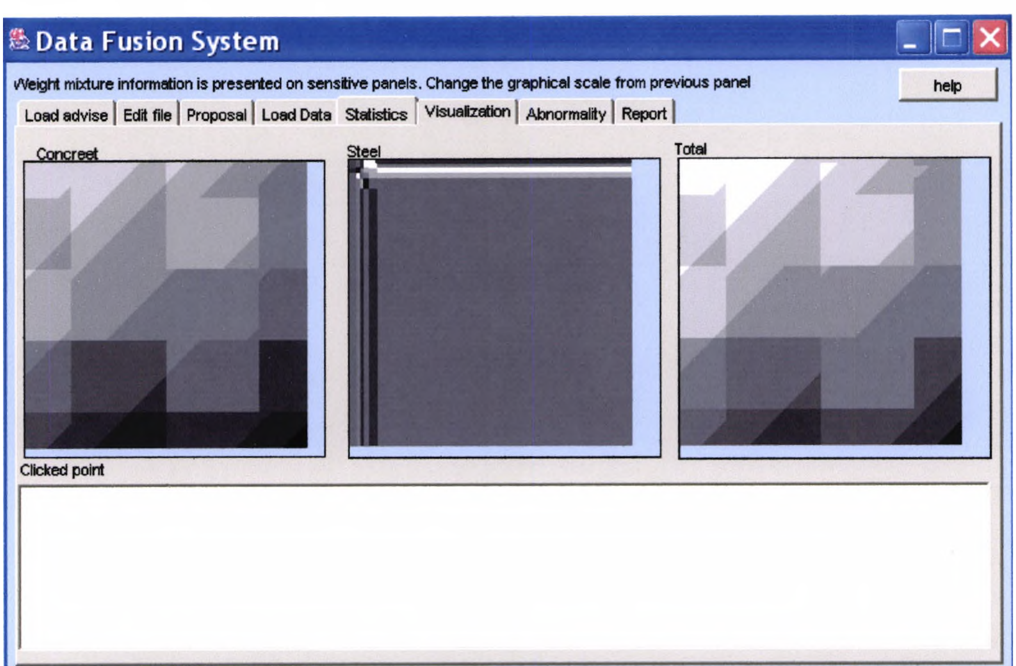


Figure (6.43) Screen 6

If more information is required for an area, the user can gain this information by clicking on that area. Both the 'Abnormality' and 'Report' screens are illustrated in the following figures, where all input and output information is presented. This can be saved for future reference, or printed out in the normal way.

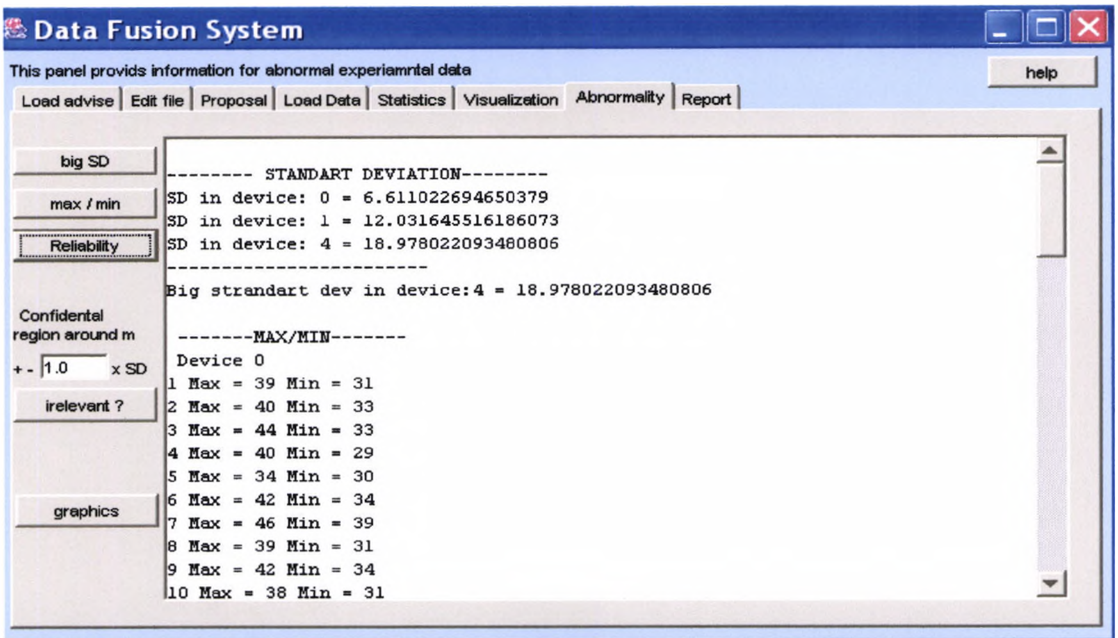


Figure (6.44) Screen 7

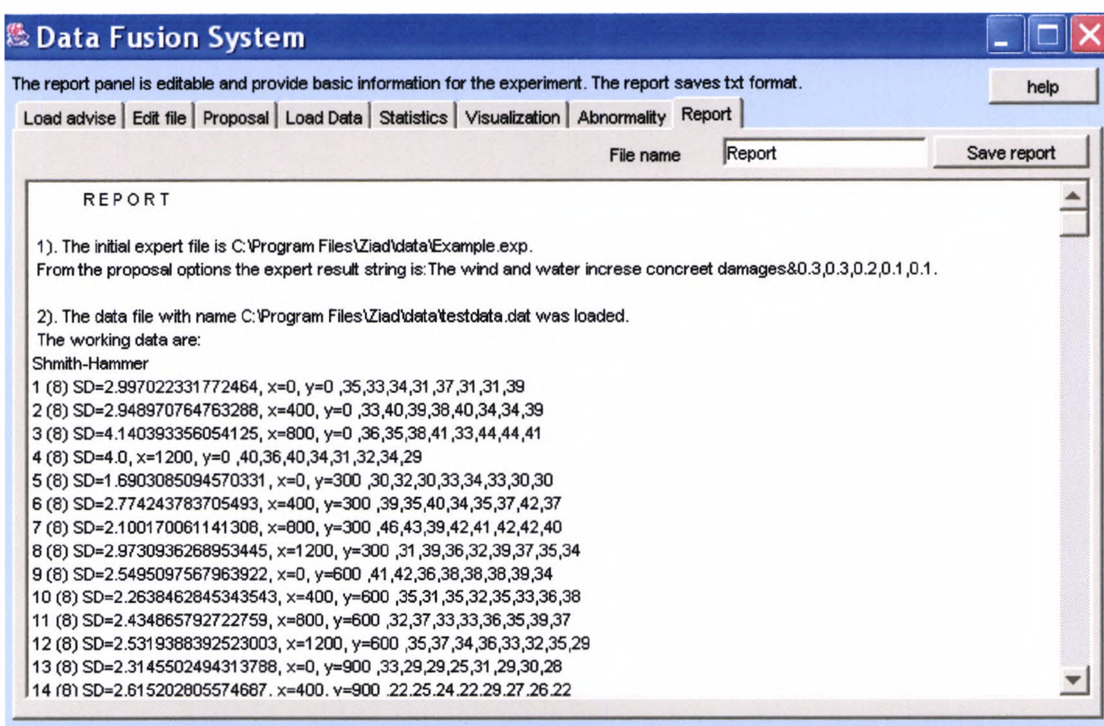


Figure (6.45) Screen 8

6.21 System reliability

The confirmation of system reliability is complicated by the need to make direct comparisons in the decision making process i.e. machine derived outcomes against the stages in expert deduction. To make an estimate possible, the author divides the decision making process into subtasks that characterise (using different parameters) the decision making process. Not only the current system's performance but the effect of future improvements to the system can be estimated this way.

According to the initial analyses in chapter 6 and figures (6.9), (6.10) and (6.11), it is possible to split the data fusion based decision making process into four main parts.

Each of them has specific meaning which is readily identified in hand calculations. These four calculation stages are:

- A. Collecting the information as precisely as possible
- B. Filtering the data for noises caused by internal or external factors
- C. Extracting information (Fuzzy logic) in an appropriate form
- D. Performing analyses and taking decisions

Following this logic, risk assessment can be performed for the system according to several parameters, comparing use with two different users (expert and novice). Conclusions on this can be made from the following table:

Comparison parameter (stage: A,B,C,D)	System + non experienced user	System + experienced user	Expert without system
Data storage and collection (A)	Automatic	Automatic	On paper or computer file
Possibility for noise reduction (B)	Manual, but the system will calculate the statistical parameters needed	Manual, but the system will calculate the statistical parameters needed	Manual and requiring time. For large amounts of data statistical calculations are impossible and semantic mistakes are likely to occur.
Monitoring sampled locations on the surface (B)	Allows monitoring of sampling locations dynamically at any time.	Allows monitoring of sampling locations dynamically at any time..	Not possible
Interpolation of points with exceptional behaviour (B)	Automatic by different algorithms and their associated precision	Automatic by different algorithms and their associated precision	Manual calculation is possible but requires substantial amounts of time.
Visualization of the surface (B)	Automatic	Automatic	Not available
Analyses on one sample for one point (B)	Automatic	Automatic	Possible but needs considerable effort
Extracting information on the meaning of a particular numerical representation. (C)	Possible if it is included in the expert file at the beginning of program execution	Possible, depending on experience	Understanding the meaning depends on the degree of expertise
Including external information (logical) in the decision making process (C)	User relies only on the expert file	Partially relies on the expert file. User can control weights and include other information	Relies only on experience.
Possibility for analyses of concrete and steel reinforcement separately (C)	Views are available with analysis for all data	Views are available with analysis for all data	Manual analyses of specific locations required. In most cases depends on the experience
Reverse analyses (B)	Available at all stages	Available at all stages	Must be recalculated manually
Final analyses generation (D)	Based on all data, with visual	Based on all data, with visual	Based only on a limited amount of data

	presentation of the surface	presentation of the surface	
Report generation (D)	All user activities are recorded	All user activities are recorded	The report has to be created from scratch
Possibility to include new knowledge (D)	No possibility, except changing weight coefficients	Based on editing the EXP file (rules) and dynamic changes in weight coefficients	Possible. Restricted only by manual processing of measurement data
Possibility to re-run data processing (D)	All processing can be re-run	All processing can be re-run	Part of the analyses can be tracked and re-examined.
A). Collecting information B). Filtering noise from data C). Extracting information in an appropriate form for the surface D). Performing analyses and undertaking the decision process			

Table (6.3) Comparison of reliability in decision making

Analysing the table the following conclusions can be withdrawn. The program initially files data better than an expert on the grounds of precision in the calculations with the input data. The program allows better presentation of data by providing full data interpolation, with graphical presentation of calculated results at any point on the surface.

The program gives the possibility for external information to be included in the model mixture, by using an expert system rule based approach in the external database. This file is editable and can be updated and saved for future use. Unfortunately, not all possibilities can be included in the expert file, this amounting to a small restriction.

The program provides excellent process tracking by saving all 'User Steps' in the final report. The program provides facilities to include external information (not included in EXP file) in the model by changing the weight coefficients. Changing these parameters has to be justified (explained) in the report because otherwise the effect would be untraceable.

The program permits fast calculation of the data and makes possible detailed analysis in a few minutes.

The program creates an environment where non experienced users can analyse previously stored information. This represents a useful tool for the novice.

6.22 Conclusions

The software has achieves improvements in the field of concrete testing and data evaluation as follows:

- Reducing the time for data evaluation,
- Raising the probability (reliability) of the results (conclusions).

During the development there were several challenges according to different factors and conditions and they have all been satisfied. In conclusion it can be said that the initial aim, to create a standalone data fusion system that increases results precision, reduces processing time and assist the comprehension of survey outcomes has be achieved.

Chapter 7

CASE STUDY

7 CASE STUDY

7.1 Introduction

A bridge in the North of Britain was tested as a case study. Its design is that of two end, cast in-situ deck cantilevers supporting a drop-in pre-stressed deck on half joints with elastomeric bearings. In the course of periodical visual inspection visual inspection it became apparent that the bridge had suffered some deterioration. The decision to undertake a detailed inspection involving non-destructive testing was taken. Extracts from the photographic record are included below to covey a sense of the condition of the bridge.

Figure 7.1 Abutment area showing rust staining

Figure 7.2 Abutment area showing exposed reinforcement

Figure 7.3 Half joint showing rust staining at bearing

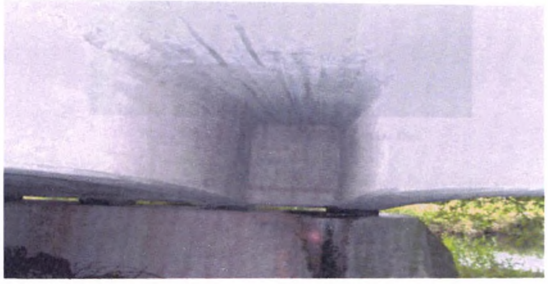


Figure 7.4 View of bearing plinth showing concrete spalling

The data for the case study experiments is contained in a separate volume of this thesis.

7.2 Inspection

Following visual inspection, locations were selected for further detailed investigation in order to quantify the condition of the structure. It was observed that the bridge bearing nips at the half joints were in poor condition, with rust staining and some concrete spalling. For this reason, the detailed inspection concentrated on these locations, where it was believed that problems existed.

Drawings showing some of the design were available to help plan the approach to gathering more information about the structure (samples figure 7.5 & 7.6). Based on the expected location and content of reinforcement, non-destructive testing was carried out.

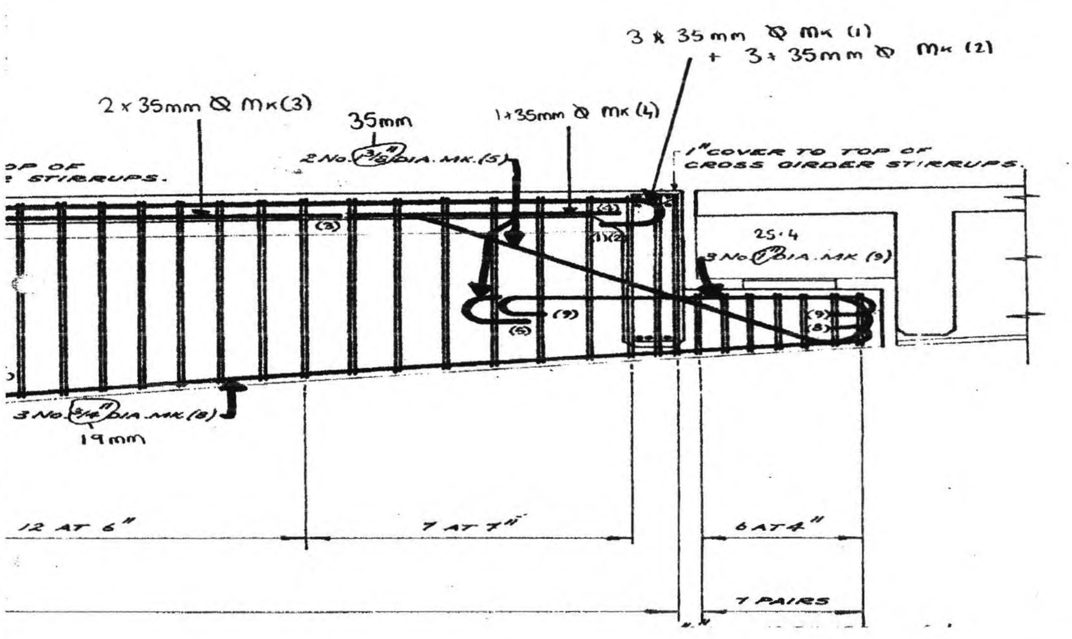


Figure 7.5 Designed reinforcing provision at half joints

It was understood that both sides of the bridge were built in the same way with identical reinforcement provision.

Observation	Orientation	End Cantilever	Drop-in beam
Surface Finish of Concrete		Smooth, damp, even finish	Smooth, damp, even finish
Orientation of Bar With Least Cover		Vertical	Vertical
Bar Diameter & Actual Cover	Vertical	31mm, 5mm,	38mm, 8.5mm
Rebars	Horizontal	Not exposed	Not exposed
Bars Type	Vertical	Smooth, round	Smooth, round
Rebars	Horizontal	Not exposed	Not exposed
Condition	Vertical	Slight surface corrosion	Slight surface corrosion
Rebars	Horizontal	Not exposed	Not exposed
Average Minimum Cover using Covermeter		35mm	29mm

Table 7.1 Summary of typical observations

Further details of concrete and reinforcement findings are given in the following tables (see also separate volume containing data).

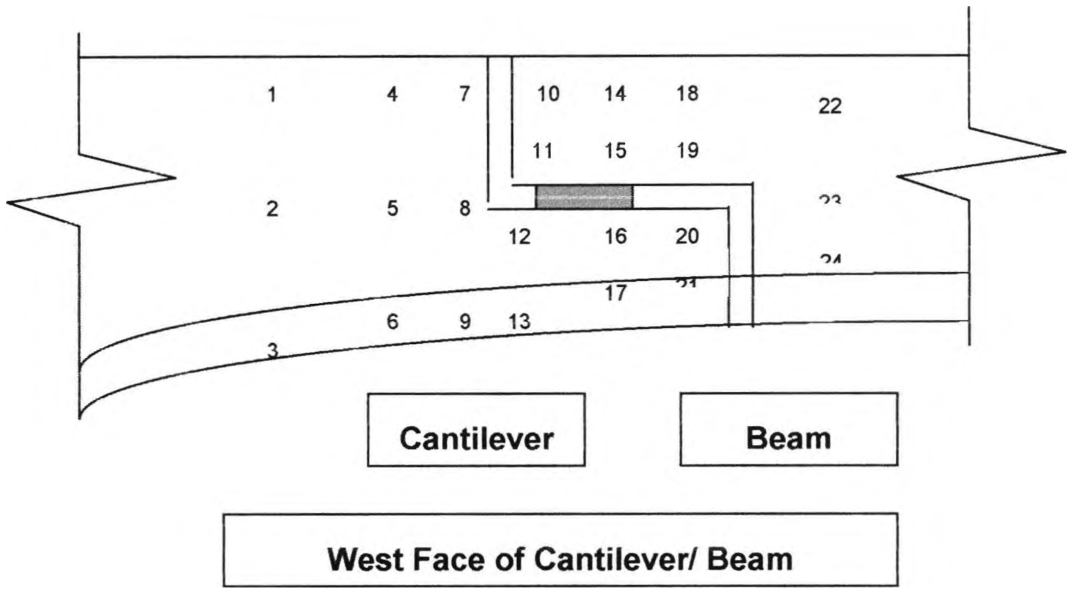


Figure 7.6 Typical pattern of survey points at a beam half joint

Six locations were chosen as examples to demonstrate the programme. The following results include readings with the NDT methods used for inspection. In the analysis, each location is indicated by its position and treated individually.

North 1: Covermeter Data (Sample)							
Point	X	Y	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
1	750	60	28	29	30	27	27
2	750	450	18	17	18	19	17
3	750	900					
4	1350	60	28	28	27	30	26
5	1350	450	19	20	18	17	16
6	1350	840	72	75	70	71	69
7	1950	60	31	31	31	32	31
8	1950	30	34	33	33	35	35
9	1800	540	28	27	29	28	28
10	1800	810	23	24	24	22	21
11	2520	60	39	40	41	36	38
12	2520	300	42	41	40	44	40
13	2400	540	30	29	28	33	30
14	2400	780	24	25	26	23	22
15	3000	60	38	39	36	40	39
16	3000	600					
17	3000	690	29	30	31	32	28
18	3750	60	53	55	54	52	51
19	3750	600	56	55	56	54	57
20	3750	690	26	25	26	27	26

Table 7.2 Sample Covermeter Data

North 1: Half Cell							
Point	X	Y	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
1	750	60	182	183	180	185	179
2	750	450	85	86	87	84	85
3	750	900	188	188	188	189	187
4	1350	60	208	205	207	202	210
5	1350	450	138	140	140	137	135
6	1350	840	326	325	327	327	326
7	1950	60	219	220	220	219	218
8	1950	30	222	221	222	221	223
9	1800	540	376	377	378	375	373
10	1800	810	381	375	374	390	379
11	2520	60	114	110	120	123	111
12	2520	300	14	20	13	15	12
13	2400	540	408	405	404	410	409
14	2400	780	374	375	374	376	377
15	3000	60	78	81	79	78	77
16	3000	600	47	50	51	49	46
17	3000	690	39	41	40	38	39
18	3750	60	81	82	81	80	79
19	3750	600	43	45	44	41	40
20	3750	690	20	25	19	16	17

Table 7.3 Sample Half-Cell Data

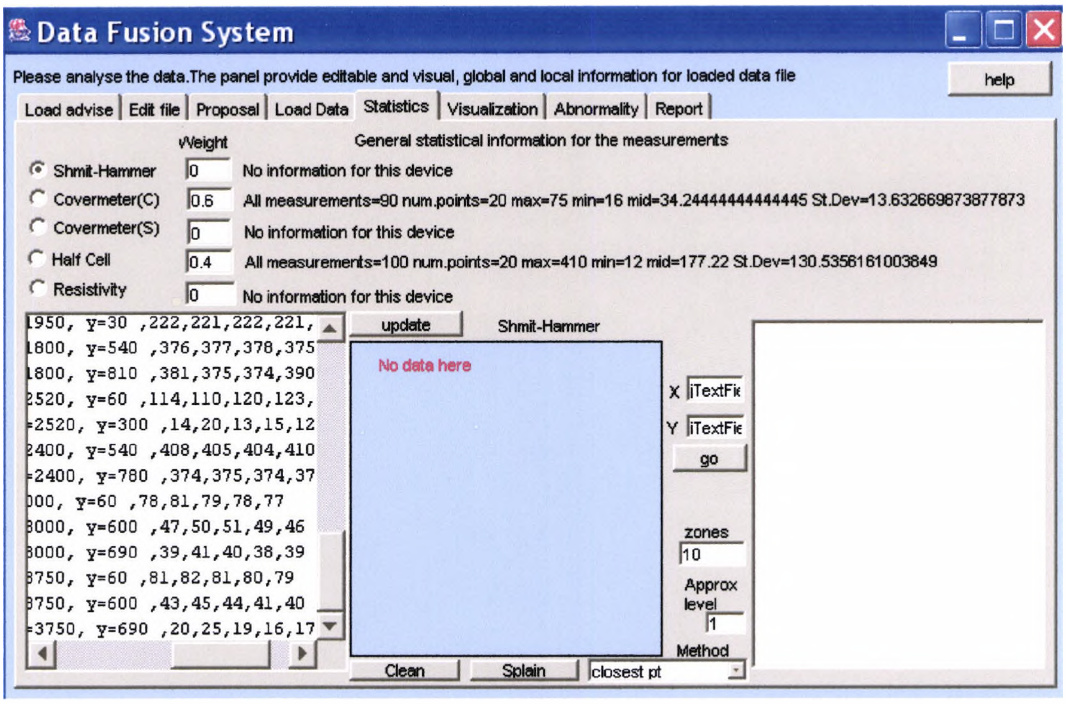


Figure 7.7 View on data processing screen

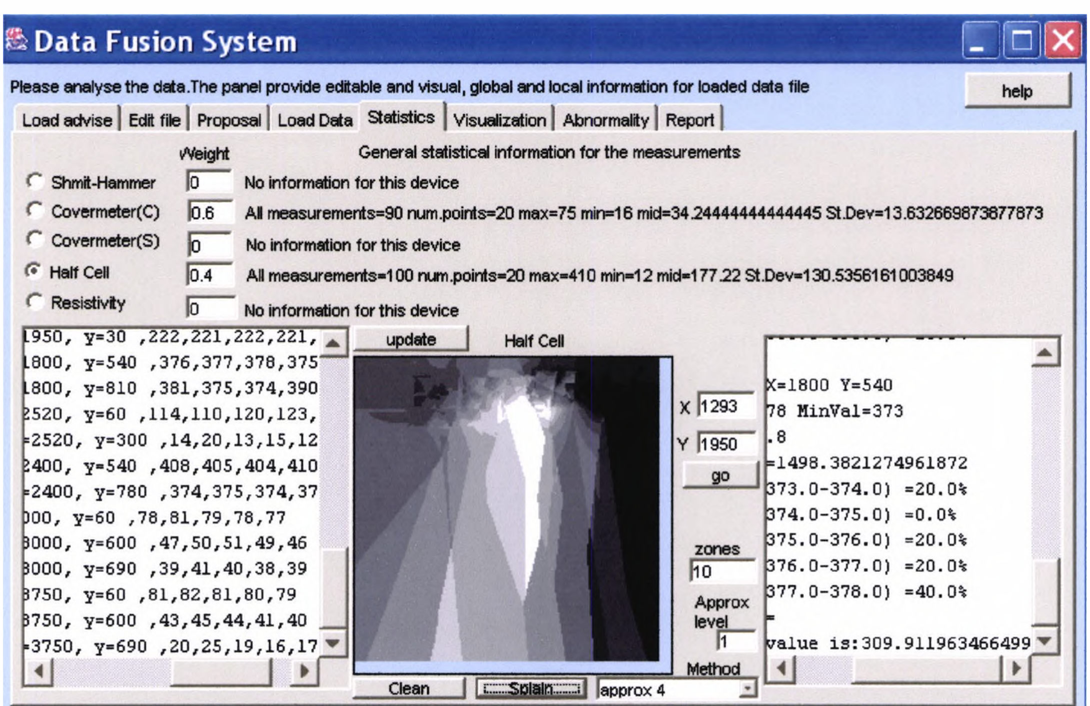


Figure 7.8 View on fused result

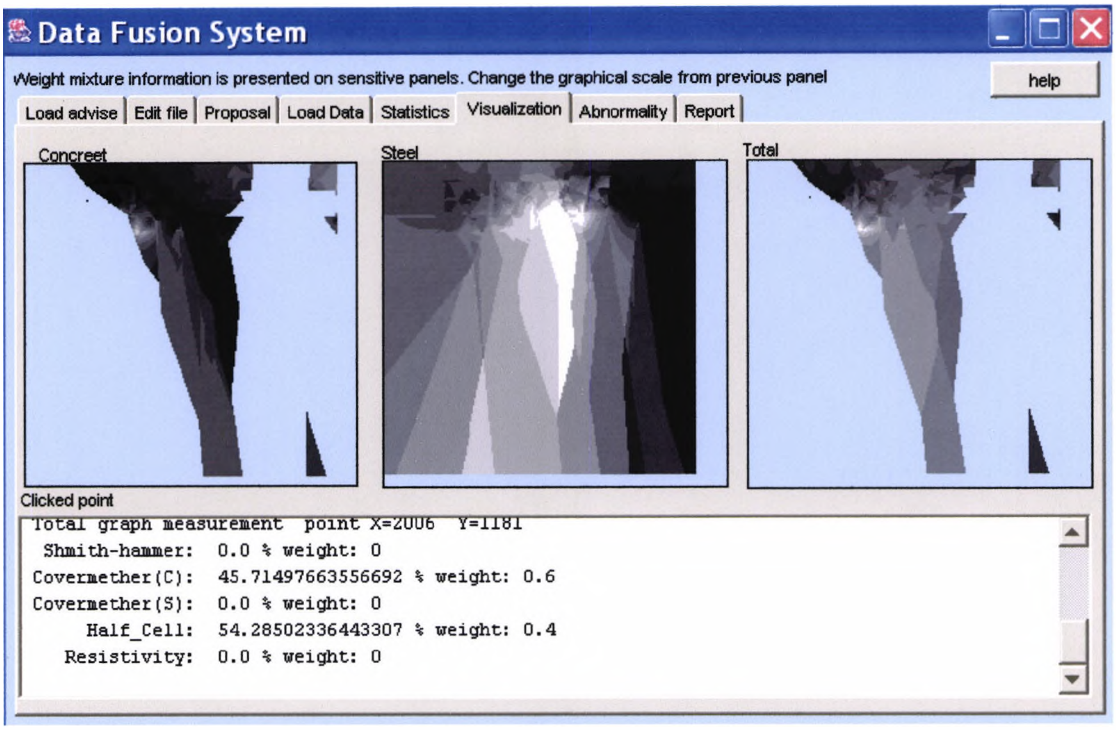


Figure 7.9 View on fused results

7.3 Conclusions

The case study, for which the data is contained within a separate volume of the thesis, has been run using the Stage 2 software tool. From this it is apparent that the system can cope with the dissimilar data (figure 7.7), giving a fused view of the condition of the half-joint nibs. The system highlighted zones of deterioration reflected by low cover and occurrences of spalling combined with significant half cell values. Areas with apparently conflicting data i.e. high resistivity coexisting with significant half-cell values were resolved by the influence of low rebar cover, giving a result that is consistent with the occurrence of spalling. Whilst outcomes are clearly dependent on user experience in the allocation of weightings, the result is objective to the extent that changes in the fused result can (figures 7.8 & 7.9)be readily assessed using the graphical interface.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The prime agents for concrete decay have been reviewed in this research. Reinforcement content; concrete cover, concrete strength and electrical potential (half-cell potential) have been adopted as the main sources of required data in the determination of condition and thus repair requirement. This reflects the universally accepted importance in everyday site non-destructive testing based investigation work.

In term of NDT methods which are associated with the required data, the various equipment specifications and features have been reviewed. While it would have been interesting have adopted a broad range of equipment, this was considered to be neither practical nor necessary for the research objectives.

The main point of the research has been to investigate fusion of NDT data, implement the core ideas in a software tool and undertake a case study using it. Two generations of software tools have been produced. In the Stage 1 version, a simplistic approach based mainly on a weighting approach was devised. Under the Stage 2 work, a substantially more complex approach has been adopted that incorporates a number of algorithms, including experts systems. A comparison has been give, indicating that the Stage 2 tool is more realistic and relevant.

Four different NDT methods have been adopted in the experimental research; half-cell potential, resistivity, cover meter and rebound hammer. They were also available and represent the most commonly used NDT methods. The data types from these are dissimilar and thus are useful to test the data fusion ideas. By contrast, data fusion systems in other fields are is typically more straightforward, being applied to the fusion of multiple sensors of the same type, for example.

The majority of the data fusion methods reviewed are not feasible for, multi-sensor systems comprising multi-type sensors. In aircraft safety system, for example, 3-4 identical sensors are used to measure the same critical quality. Here, the role of data fusion is typically to add confidence to go/no-go voting states. For this reason, the author had investigated an approach which is broadly a combination of the statistical and weighted methods. This approach has been encoded and reported as the so-called Stage 1 model which was implemented using visual basic and excel.

In the Stage 2 model, subsequently investigated, a combination of Bayesian logic and expert systems has been added to the Stage 1 model. This experimental software programme has been shown to work well and is useful in investigations into weighted combinations, giving different views on the concrete condition problem. Ideally, the data should be processed into a single condition parameter number but the meaning of this unclear, being a function of the causal knowledge that is incorporated into the process. Rather than target on absolute outcomes, a statistical backbone based on certainty has been adopted in the research..

By creating this application, several improvements in the field of concrete testing and data evaluation can be achieved as follows:

- Reducing the time for data evaluation.
- Raising the probability of the results (conclusions).

In the course of the research several challenges have been posed and successfully addressed as follows:

- Addressing human-machine complexity, which leaded to the development of a human friendly virtual environment.
- Development of data evaluation by mixing mode.
- Development of new mathematical tool for data visualisation.
- Development of parsers for data input/output operation and. analysis.
- Development of a rule based approach to handle initial noise reduction and the knowledge database.
- Development of data evaluation using statistics methods.

In conclusion it can be said that the goal which was to create a standalone software tool for data fusion, to increase the results precision and support interpretation and conclusion building in substantially reduce time has been fulfilled.

The Stage 2 application combines several approaches for data evaluation starting with a rule based approach, statistical evaluation, visual evaluation and model mixing. The system is high flexibility and useful human-interaction mechanism towards the formation of the final decision on concrete condition and corresponding repair requirement.

The experimental system was tested with different artificial and real data and found to be stable. The system supports novice and inexperienced NDT surveyors because it does not require expert knowledge in non-destructive concrete testing,

The re-usability of the approach is high due to the adoption of independent 'soft' coded algorithms. This means that such system can be adapted for different purposes and conditions, simply by replacing the existing knowledge database. In a sense it is like the well established expert system shell for which any domain software can be incorporated.

8.2 Recommendations

To improve the prospect for industrial exploration of the data fusion approach, several developments can be identified:

Control of user input: User input is a time consuming activity for industrial artificial intelligence needs to be provided to support this, providing a stable easy to use regime.

For simplicity, the experimental software can only operate with integer values, which is not very practical. This needs to be corrected with free ranges of data type allowed.

In the experimental system, for simplicity, it was assumed that the larger numbers are better for the system (the mixed model). A simple example for this is resistivity, which delivers 2-4 digit data. The simplest way to avoid this problem is just to input the inverse number data. Because this would decrease the system flexibility and re-usability, the author avoided including this data mechanism.

8.2.1 Possibilities for communication and multi-user tacking

It could be advantageous for many different users to use the system simultaneously. This would require a web environment. It is envisaged that the tool is more likely to be server application rather than standalone.

Creation of the experimental data fusion tool creates gives the possibility for investigations into other fields of application. High re-usability in the tool permits the system to be applied in different areas which involve complex calculations, communication and visual appreciation to support data based decisions, for example.

Finally the experimental tool only covers basic requirements in the processing and interpretation of non-destructive data. Substantially greater knowledge could be accumulated with more experimentation and use. More case studies should be addressed including ones involving other sensors than the four employed.

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