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An innovative user-centred support tool for Augmented Reality maintenance systems design: a preliminary study

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Abstract

Augmented Reality (AR) technologies in maintenance are demonstrated to positively impact on technicians' work and performance. Current research in this area is mainly focused on solving technical challenges related with AR in industrial environments. Limited attention has been put into the user perception, ergonomics and usability aspects of AR systems design. This paper proposes an innovative user-centred design support tool for AR systems in maintenance contexts. The tool is based on the Analytic Hierarchy Process (AHP), which is a well-established multi-criteria decision-making approach. In this research, AHP is utilised for guiding designers in the evaluation of application-contexts and AR-technologies for selecting the most suitable and effective AR interaction solution. The tool's validation has been conducted with twelve maintenance-experts in a design workshop using two case studies. The quantitative results obtained in both case studies reveal the applicability of the AHP model, as well as the effectiveness of the design support tool for complex decisions in AR for maintenance. The use of AHP methods for AR design enable experts to deal with complex and contrasting concepts and express a preference among them with a subjective judgement based on their personal understanding of the problem. Therefore, simplifying the design of AR systems for complex maintenance contexts.

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Keywords: Augmented Reality; Maintenance; Systems Design; Analytical Hierarchy Process.

1. Introduction

A constant concern in maintenance is maximizing availability and safety at the minimum cost [1]. This, along with growing asset complexity [2], is increasing the difficulty of maintenance processes and its dependency on maintainers' expertise. The need of skills and knowledge for task-execution effectiveness demands new technologies to support maintainers while performing their tasks.

Augmented Reality (AR) is a technology meant to enrich users' real-world experience [3]. And maintenance is one of AR's most addressed and researched fields of application [4]. AR provides real-time support to maintainers by embedding information into their interaction with the assets to maintain [5]. Therefore, AR can help to increase safety and/or reduce cognitive workload, errors and/or duration of tasks.

Nevertheless, AR research remains at an exploratory stage [4]. Most AR-maintenance research is focused on the development of case-based specific applications. There is less attention to design methodologies and even less from user-centred perspectives. Therefore, this research aims to develop and validate a user-centred design support tool for AR maintenance systems' interactions. The basis of this method is to analyse and evaluate potential AR solutions for specific contexts, using the Analytical Hierarchical Process (AHP).

The rest of the paper is organised as follows. Section 2 reviews the literature in AR systems design and user-centred methodologies. The design support tool, based on the AHP model, is presented in Section 3. Section 4 describes the test cases used to validate the design tool. The analysis and discussion of its results are conducted in Section 5. Finally, Section 6 presents the conclusions and future works.

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2. Literature Review

Research in AR applications is attracting more attention nowadays. The increasing maturity of AR technologies enable their usage for an extended number of applications [6]. In case of maintenance, these applications are varied (e.g. repair assistance, assembly design, human-robot collaboration, etc.). A number of literature reviews [3,5,7] describe them in more detail. These reviews identified a common trend among the AR-maintenance applications. Even though they attempt to improve similar targets (e.g. efficiency increase, time and errors reduction, etc.), the AR-maintenance applications are case-specific and do not follow general design principles.

A number of literature reviews in various AR fields of application (marketing [8], medicine [9], learning [10]) show diverse design challenges in each field. Still, compared to others (e.g. learning [11]), no general design principles have been found in AR-maintenance. A logic reason for this can be the differences in AR-maintenance case studies. Most cases are very different to one another, as they focus either in different maintenance processes (e.g. repair, diagnosis, etc.) or maintaining assets (e.g. engines, machine tools, warships, etc.). Therefore AR-maintenance literature has proposed a different approach. Instead of using general principles, AR-maintenance research has developed different evaluation methods. These methods are focused in different aspects of AR-maintenance applications such as hardware [12], software [13] and performance [14,15]. Generally, these methods follow one of the two following approaches:

- Select the best combination of hardware and software to determine an AR solution for a given maintenance application [12,13].
- Evaluate the performance of a given AR solution in a specific maintenance application [14,15].

Even though these two approaches seem different, they attempt to solve the same problem: a multi-criteria decision to define an AR solution (hardware and software) for a given maintenance application. Methods and criteria utilised to solve this problem are still part of current research in the area. For the methods, there already exist comparisons and evaluations for their suitability regarding the kind of problem ([16]). For the criteria instead, there are still research gaps regarding the types to utilise and the kind of problems to focus on. The kind of problems in AR-maintenance are the two approaches mentioned above. Nevertheless, the types of criteria are more varied and not all have been considered. There have already been considered performance-centred [12], technical-centred [14,15] and information-centred criteria [13]. But to the best of author's knowledge, there has been no proposal in such AR-maintenance decision-making problem with user-centred criteria. Even though user-centred criteria can be found in research for performance evaluation [17], the authors could not find any records of its application to the decision-making problem for AR-maintenance systems design as stated above. Thus, it can be said that there is lack of research on applying user-centred criteria to the design of AR maintenance systems, specifically in the selection of hardware and/or software.

To contribute to the fulfilment of those gaps, this research aims to apply user-centred criteria to the selection of AR hardware solutions for maintenance applications. Two considerations are important for the approach taken by the authors. First, this paper considers the application of existing decision-making methods. The target is to use the Analytical Hierarchical Process (AHP), reported as valid in various papers [12,15]. Second, this paper attempts to develop a design support tool for defining AR hardware solutions independently from existing AR devices. In order to do so, the AHP-based tool focuses in AR-interactions instead of AR-hardware solutions. Thus, the tool is not dependant of existing devices. The rationale of this decision is explained in Section 3.1. Once the design method proposed is validated, it could be extended to other design-related research gaps (e.g. software selection).

3. AR-Interaction User-Centred Decision Support Tool

Saaty [18] presents the Analytical Hierarchical Process (AHP) as a "decision making tool based on pairwise comparison of intangible criteria and subjective judgement of experts to derive priority among alternative solutions". Compared to other multi-criteria decision methods, AHP is easy-to-use, scalable and not data intensive [16]. Therefore, it suits the needs of AR designers to prioritise among solutions regarding different levels of criteria, which are interdependent. The AHP method consists of the following four steps [18]:

1. Define the problem (AHP-1).
2. Structure the decision hierarchy (AHP-2).
3. Construct a set of pairwise comparison matrices (AHP-3).
4. Analyse the final priorities of the alternatives (AHP-4).

In order to fulfil this research's aim, these four steps were applied to the selection of AR-maintenance interaction solutions from a user-centred perspective. The application of each step is described in each of the following subsections.

3.1. AHP-1: AR-Maintenance Interaction Solutions Selection

Gaps identified in academic literature suggest to propose a multi-criteria decision approach for AR-maintenance hardware solutions selection focused on a maintainer's perspective. To avoid current devices dependency, the research scope narrows to the selection of AR-interactions for AR systems design.

Several publications [3,5,7] have identified different classifications of AR devices (hardware solutions). Nevertheless, rapid advancements in commercial technologies (e.g. HoloLens, Google Tango, etc.) make these classifications obsolete. To avoid this obsolescence, the authors decided to select AR interactions (e.g. visual) instead of hardware (e.g. tablet). The arguments that favoured this decision are below:

- **The type of results given by AHP methods:** these results are percentages of the alternative solutions proposed. If the alternatives are AR devices, then the method has to change to consider any new devices. Instead, if the alternatives are AR user-system interactions, the method can remain and adapt the results obtained.

- **The need of user-centred view on AR solution design:** in order to apply user-centred criteria, it is easier to select between AR interactions (directly related to the user) than between AR devices (related through the interactions).
- **Independency from existing AR devices:** selecting between interactions instead of devices would make the prioritisation more generic. Therefore, the tool could be used along the evolution of AR devices. So, when ranking the solutions, AR systems can have with multiple.

Hence, the outcome of AHP-1 (problem definition) is as follows: *"Determine the most effective AR interaction type for any given context of use (maintenance application) and user (maintainer)"*.

3.2. AHP-2: Hierarchy of Maintainers-Centred Criteria

As said by Saaty [18], the target of AHP-2 is to determine the variables (criteria) as well as the alternatives (AR interactions) to consider in the decision-making process (solution selection). In order to do so, a hierarchy must be set to structure these variables from the goal (selection) to the alternative solutions by levels of specificity. Similar researches [12,15] have defined three levels of specificity in which classify the variables (user-centred criteria). The first level (criteria) is generic and identifies the design requirements of an AR system. Second and third levels (criteria) are more specific and translate the design requirements to AR interaction attributes (user-centred criteria). While previous research used the SCOR model [19] to define the criteria, this research proposed a different approach considering existing standards (ISO 9241). The criteria selected in AHP-2 is described below.

Based on existing standards for Human-Computer Interaction (HCI) systems, a set of criteria regarding a maintainer-centred perspective of AR systems was defined. Then, these criteria were validated by six AR-design experts through a questionnaire to identify which were relevant for maintenance applications.

A common standard for HCI is ISO 9241, focused in the ergonomics of HCI. As a HCI technology, AR can use it to define the design factors of AR systems and the attributes to consider for selecting AR interaction solutions. Based on the problem definition given in Section 3.1. the part of interest is ISO 9241-11, related to guidance on usability. ISO 9241-11 provided the factors (second level criteria) and attributes (third level criteria) for the design of AR interactions based on usability principles (first level criteria) – adaptability, appropriateness, effectiveness and operability.

For these four principles (first level of criteria), the ISO 9241-11 provides factors and attributes for interactions classified in three groups (environment, situation and interaction). These groups (Figure 1), as well as the factors (second level) and the attributes for each factor (third level criteria), are described below (according to AR systems):

- **Environment:** the real-world context in which the AR application takes place. It refers to the physical properties (e.g. position, light, etc.).
- **Situation:** the real-situation context in which the AR application takes place. It refers to the situational properties (e.g. task, user, object, etc.).
- **Interaction (AR system):** as a HCI application, it refers to the software (interaction) and hardware (ergonomics) properties of the AR solution.

From the Environment factors, user location has been considered as relevant:

- **User location:** refers to the physical environment that may influence the AR interaction. The physical environment defines the working conditions, which are divided into two main categories (attributes): place and environmental attributes. Place describes the space in which a task is executed: indoor or outdoor. The environmental attributes are six: working space, noise level, visibility level, risk level, humidity level and weather conditions.

From the Situation factor, user profile and user task have been identified as relevant:

- **User profile:** refers to the description of the AR user. To achieve the highest levels of effectiveness, efficiency and satisfaction, the AR interaction must be adaptable to the widest range of people. The user profile is described by four elements (attributes): task-experience level, computer-experience level, system-experience level and physical capabilities/restrictions of individuals.
- **User task:** an appropriate input AR interaction enables the user to achieve the required effectiveness for the task and is efficient and satisfactory for the intended population (ISO 9241:410 2008). A general maintenance task (e.g. repairing, monitoring, etc.) can be described by these attributes: operation time, frequency, cognitive effort level, physical user-mobility required and knowledge type.

From the Interaction factors, user inputs/outputs, and user cognitive ergonomics have been classified as relevant:

- **User inputs/outputs:** "a sequence of user actions (inputs) and system responses (outputs) in order to achieve a goal" (ISO 9241:110 2006).
  The interaction modes (user inputs) are: gesture (hand movement), tactile (touch sensitivity), vocal (speech recognition), and gazing (eye movement).
  System responses (outputs) refer to the information (augmented content) to be provided. Apart from the format of such information, it can be classified as static (predefined) or dynamic (real-time updated, data).
- **User cognitive ergonomics:** while designing AR systems to support human-computer interaction, it is essential to consider the comfort and efficiency in the working environment. The following attributes (factors) describe the ergonomics for AR devices: usage time, cognitive workload and physical comfort.

The validation of relevant factors and attributes identified in ISO 9241-11 from an AR design perspective was conducted through a questionnaire with six AR-design experts. Table 1 presents the outcomes from the questionnaire. Those answer considered as relevant by four or more AR-experts were selected as critical and included in the hierarchy (are bold in the table). Those which not (selected by three or less experts) were rejected from the hierarchy.

Table 1. AHP criteria validation: AR experts' questionnaire outcomes

Which are the elements to consider while designing a new AR solution?					
Environ-ment	**Experien-ce**	**Task**	**Informa-tion**	**Interac-tion**	**Ergonomics**
Which are the environmental conditions to consider while designing a new AR solution?					
Hazardous	**Noisy**	**Weather**	**Space**	**Light**	**Humidity**
Which are the user's attributes that can affect the design of AR solutions?					
Task experience	Computer experience	Device experience	Physical limitations		
Which elements of a task must be considered while designing a new AR solution?					
Frequency	Operation time	**Cognitive effort**	**Physical mobility**	**Knowledge type**	
Which are the Interaction Requirements to consider while designing a new AR solution?					
Interaction mode	**Information type**	**Ergonomic attributes**			
Which are the main categories of interaction?					
Gesture	**Tactile**	**Vocal**	**Gazing**		
Which are the type of information to consider while designing a new AR solution?					
Static	**Dynamic**				
Which are the ergonomic aspects to consider while designing a new AR application?					
Usage time	**Physical comfort**	**Cognitive workload**			

To finalise the AHP hierarchy model, the alternative solutions have to be defined and linked to the factors. These solutions relate to the user-system interaction type provided by the AR hardware. They are not related to specific AR devices:

- **Visual solutions:** the information is displayed in a visual way. It means the designers must focus on the visual sense, without excluding other senses. Visual information is: text, 2D/3D static/dynamic symbols, video, etc.
- **Aural solutions:** the information is presented as sound. It means the designers must focus on the aural sense, without excluding other senses.
- **Haptic solutions:** the information is presented as haptic (touch and proprioception) feedback. The designers must focus on these, without excluding other senses.

These alternative solutions complete the hierarchy model that is presented in Figure 1.

3.3. AHP-3: Maintenance-Experts Pairwise Comparisons

At this point of the AHP method, the design support tool is already defined. It is at this stage when the tool is used by AR-maintenance experts. It allows them to provide in a structured manner their individual understanding of the application of AR into the maintenance context. This structured manner is the pairwise comparisons. These clarify the relative importance of the criteria at the same level with respect to the upper level in the hierarchy model (Figure 1). The results are priority values used for weighting the priorities of the alternative solutions.

The process as well as the numerical scale used to make pairwise comparisons was also defined by Saaty [20]. These were already well-described by Saaty in his article "Decision making with the analytic hierarchy process" [18]. This research was only limited to the application of those. A total of 33 pairwise comparisons (1 for the first level criteria, 4 for the second level criteria and 28 for the third level criteria) are given in the form of a questionnaire to the AR-maintenance experts to provide their subjective understanding.

3.4. AHP-4: Design Selection of AR Interaction Solutions

The results given by the experts' pairwise comparisons (Section 3.3) provide the numerical reasoning to calculate the prioritisation among solutions (AR-interactions) in form of percentages. As the results are based on experts' opinions, they are subjective.

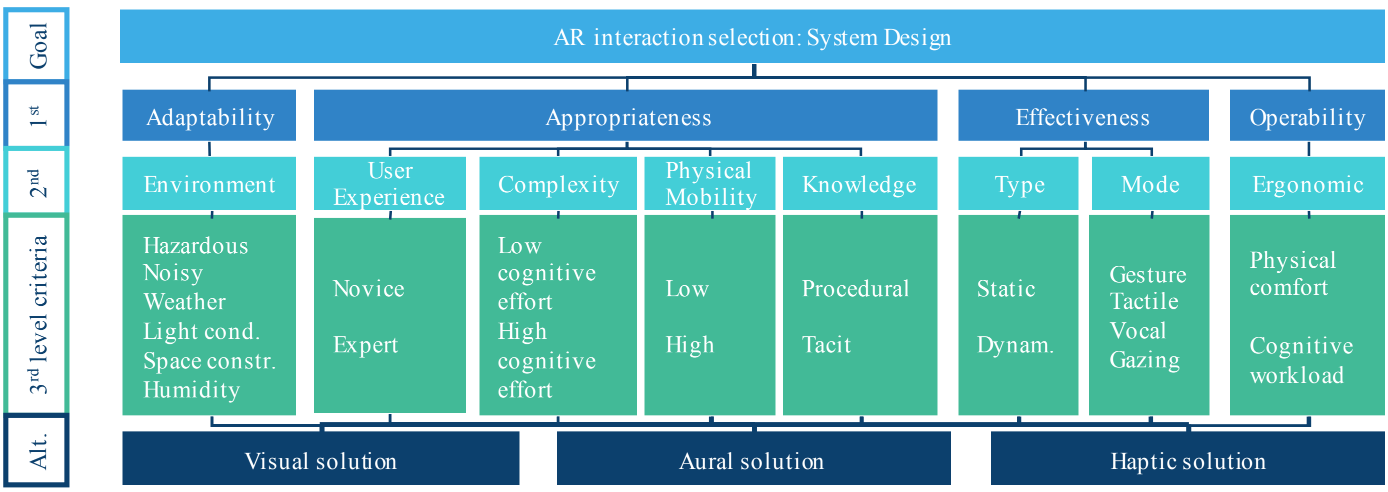

Figure 1. Hierarchy model for user-centred AR interaction solution

Saaty [20] also proposed a way to evaluate the subjectivity in order to verify the consistency of the results. It is called Consistency Ratio (CR) and calculates the variability in pairwise comparisons' results provided by different experts. When the CR is equal or greater than 10%, then that pairwise comparison can be considered inconsistent. If that happens, then the experts are required to repeat the comparisons.

4. Validation Test

In order to validate the design support tool proposed, a test was conducted with two different AR-maintenance design case studies. The results given by the tool were compared with the solutions previously provided by AR-maintenance experts to those case studies. The comparison between test results and experts' solutions was used to analyse the validity of the tool.

The testers consisted of a group of 12 people who choose to attend the "Design of AR applications" workshop in the CIRP Design Conference (09/05/2017) at Cranfield University. The group was composed of AR researchers (40%), industrial experts (40%) and engineering students (20%). For the purpose of this study, they were taught in AR and maintenance to provide a minimum background. This was done to enable the comparison between test results and experts solutions [12]. The validation method is detailed with the following list:

1. **AR technologies presentation:** to offer all testers the same background in AR technologies.
2. **Design methodology presentation:** to offer all testers the same background in the design methodology to use.
3. **Case studies presentation:** to offer all testers the same experience in the case studies maintenance scenarios.
4. **Criteria pairwise comparison presentation:** to explain testers how to use the pairwise comparison questionnaire.
5. **Criteria pairwise comparison judgements:** testers to complete the pairwise comparison questionnaire for one of the two case studies (being randomly allocated).
6. **Results calculation**: testers' results and consistency ratios to be calculated and aggregated to provide the solutions' ranking using the design tool.
7. **Solutions comparison:** to discuss the validity of the tool by comparing testers' solutions with experts' solutions.

The results calculation and discussion comparison is detailed in Section 5. The following subsections describe the case studies utilised in the test and their experts' solutions.

4.1. On-Site Repairing and Diagnosis

This case study focuses on the corrective maintenance of a warship gun. The working environment can be described as a small indoor space, with lots of various equipment. Maintenance activities are carried out in limited spaces, with light constraints. There are lubricant leakages and the working area has high risk and noise levels. On-site maintenance activities are the repairing and controlling of equipment status in the gun. They require high levels of expertise as they involve complex disassembly operations.

The experts' solution for this case study was a combination of visual (70%) and aural (30%) solutions. It was a tablet-based AR maintenance interactive manual that provides 3D animations for procedures and sound signals for alarms.

4.2. Off-Site Repairing and Diagnosis

This case study focuses on the unplanned maintenance of a machine in an industrial plant. The working environment can be described as an illuminated, indoor, big space with machines displayed all over it. Off-site repair and diagnosis is carried out by non-experienced operators who consult remote experts about the exact procedures and tasks. Not specific levels of expertise are required for the operators to conduct these operations. The operator is connected to an expert, which receives the information on the state of the machine and gives the information to the user on how to perform a task.

The experts' solutions for this case study was a different combination of visual (50%) and aural (50%) solutions compared to the first case study. The information about the machine's state is transferred by voice while the specific spatial locations and steps of repairing were given by 3D animations. The solution was also a tablet-based AR remote application.

5. Results and Discussion

Figure 2.a and Figure 2.b present the design tool tester results for both case studies, while Figure 3.a and Figure 3.b present their consistency analysis.

Testers' solutions (Figure 2.a and Figure 2.b) are very similar to experts' solutions. For both, combinations of visual and aural solutions are similar in numbers. The only difference is in the consideration of haptic solutions. Testers' results provide relative importance to these, while experts do not consider them at all. The reason provided by experts to not consider haptic solutions was the increased difficult for AR development. Besides, the logic to prioritise visual and aural solutions with those percentages over haptic can be based on the nature of maintenance instructions to consider. The more procedural the instructions, the easier to use visual solutions. Moreover, the more complex tasks and environments, the more support to aural or haptic solutions. Overall, the testers' results are similar to the experts' results. This similarity helps to indicate validity of the design tool.

The consistency analysis for case study 1 and 2 are presented in Figure 3.a and Figure 3.b, respectively. Each graph shows the Consistency Ratios (CR) for each of the 33 pairwise comparisons conducted by testers. Only few are above 10% (inconsistent), but the case study means are 3.3% and 3.5% respectively. Thus, the results can be considered consistent. Still, these differences could be explained by the different backgrounds from the decision-makers involved in the process.

Figure 2. Testers' solutions ranking for (a) case study 1 and (b) case study 2.

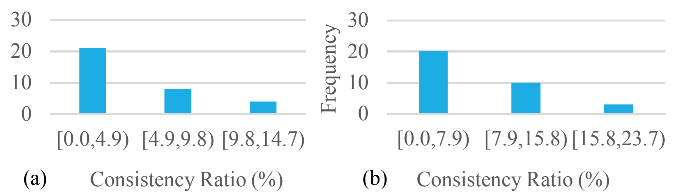

Figure 3. Consistency analysis for (a) case study 1 and (b) case study 2.

Overall, these results suggest the validity of the design support tool. Nevertheless, there are some topics to discuss about its applicability and the limitations of validation tests. First, testers' sample size cannot be considered significant according to the population targeted. Therefore, the results can only be considered preliminary and further experimentation is required to achieve final demonstration. Second, the use of random testers is not an obstacle for validation. They are given a minimum background, so they can be considered 'experts' for the tests. Thus, their results are comparable to the experts' solutions. If both are similar, then those results indicate validity of the tool. Third, experts' solutions percentages were calculated based on their AR-maintenance systems' designs. Those percentages were obtained dividing the instructions given with each interaction by the total amount of instructions given to users. Besides, this method could be replicated with any case study where those numbers can be calculated.

6. Conclusions and Future Works

This research's aim was to contribute to design of AR-maintenance systems with user-centred criteria for the selection of AR-hardware independently from existing AR devices. In order to do so, a design support tool, based on the AHP method, was developed to consider user-centred criteria for selecting between AR-interactions. It gives as result a combination of visual, aural and haptic solutions that designers can use to select between current AR devices at the time of selection. Tests with two maintenance case studies have been conducted to validate the design support tool. Twelve testers were given a background in AR-maintenance to compare their tool results against the solutions designed by experts. Due to the testers sample size the results obtained suggest validity of the tool, but further experimentation would be required for demonstration. Thus, it can be concluded the tool contributes to research in AR-maintenance design as a preliminary study were user-centred criteria is used to select AR-hardware independently from existing devices. The user-centred criteria is agnostic to different sectors. So, there is no reason to believe the tool won't apply to various maintenance sectors. Nevertheless, further experimentation with different case studies would be required.

A number of future work suggestions can be made. First, further experimentation with different case studies and testers is required to demonstrate design tool's validity. Second, further research on the user-centred criteria and the solutions' categorisation is advised to extend the applicability of the design tool. The more technical and detailed the criteria and solutions are, the most support designers will receive (e.g. select video definition and sound levels of interactions). Third, research on the relation between user-centred criteria and other criteria such as performance- or information-centred. This will help to extend the level of consideration of other important areas in AR-maintenance design. Fourth, research on extending the design support tool for other design aspects such as AR-software. This will help to provide a comprehensive design support tool for the solutions design of AR in maintenance.

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