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UX-Driven Methodology to Design Usable Augmented Reality Applications for Maintenance

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Abstract. In recent decades industrial development has led to increasingly sophisticated machinery and systems, which require complex maintenance routines. Consequently, maintenance operators may not have the sufficient skills to perform recovery procedures properly and quickly, so that the need of assistance from the manufacturer's after-sales service or companies specialized in maintenance services. Such actions usually lead to very long recovery times, high maintenance costs, and a temporary drop in production. In this scenario, we should consider that Industry 4.0 is making available innovative technologies, such as Augmented Reality (AR), suitable for improving the skills and competencies of operators without burdening their cognitive load, and consequently wellbeing. However, technologies must be selected, designed, and used according to the users' needs to be effective and useful. The paper presents a user experience (UX)-driven methodology for designing user-centric AR applications for complex maintenance procedures. The methodology was applied to a real industrial case concerning the management of CNC machines in a plant producing tractors components, where a smartphone-based AR application was designed and tested with users. The satisfactory results highlighted the potential benefits of AR in industry and specifically in maintenance.

Keywords. Augmented Reality, Industry 4.0, Operator 4.0, User experience design, Maintenance

Introduction

Industry 4.0 (I4.0) is a term coined by the German government to describe the integration of advanced technologies into manufacturing and production processes, from Big Data and Analytics to Autonomous Robot, Simulation, System Integration, Industrial Internet of Things (IIoT), Cloud, Additive Manufacturing and Augmented Reality (AR) [1]. The goal of I4.0 is the creation of smart factories as companies that can meet consumer demands in terms of customization, time-to-market and quantity [2]. Nowadays we are witnessing a further evolution trend within I4.0, called Industry 5.0 (I5.0), based on human-centricity, resilience, and sustainability, as defined by the European Commission. It suggests that available technologies should be adapted according to the needs of

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workers to ensure their well-being, mental health, and physical health [3]. In the smart factory, modern operators often find themselves interacting with both automated lines and individual machines. In both cases, human-machine interaction is complex and multifaced. In fact, production drops, errors, downtime, production interruptions, and any type of failures to meet the production goals can occur due to several factors, mainly related to machine usability problems, poor user experience, insufficient operator knowledge, and inadequate training procedures [4]. In such context, maintenance operators are technicians who use a variety of equipment and tools to fix the problems on certain equipment: they are usually required to detect the cause of fault rapidly and to follow specific procedures to restore the machine quickly, reducing the downtime. In this scenario, the most common problems can be divided into four macro-areas: Assembly / Disassembly, Repair, Inspections / Diagnosis, and Training [5]. Assembly and Disassembly of components are increasingly complex and difficult when performed following instruction manuals, so they can result in errors and longer task execution times [6]. Repair means operations aimed at the functional restoration of a device through the replacement or remanufacture of one or more components. Inspections / Diagnosis refer to checking the state of the product, analyzing, and evaluating its possible deterioration. Training is understood as the transfer of technical knowledge to new operators [5].

In the I4.0 context, novel AR applications can be used to support manufacturing operations and leverage the operators' skills [7]. AR is characterized by the superimposition of virtual objects on the real environment for different purposes: 1) to interact with combined environments including virtual and real objects, 2) to interactively perform real-time registration of the combined mixed scenarios, and 3) to recognize and correct the alignment of the virtual world with the real world. This definition is irrespective of the type of device used to concretely display virtual objects [8]. The objective of this research is to define a methodology to adopt a user-centric approach to design usable and useful AR applications able to support maintenance operators. The proposed methodology can be defined transdisciplinary since it adopts systems thinking approaches (e.g., by considering a real world problem in terms of its entirety and interconnections, rather than reducing it to its individual components) and uses collaborative design approaches, combining technical aspects (e.g., about the AR application development) with human and socio-related aspects (e.g., about the users' needs investigation and evaluation thanks to inclusive design practices), diversely from the currently adopted approaches. As a result, the proposed method incorporates social and environmental criteria and merges different research fields, from human factors to computer science to manufacturing [9]. Thanks to such transdisciplinary engineering (TE) framework, such a work supports the extension of the operator's skills in the modern factory, towards the concept of Operator 4.0 [10].

1. Related works

As far as maintenance operations are concerned, AR can be validly used to support and assist technicians in their work, by showing useful information in a contextual way and making the procedures more digital, interactive, and easier to follow, reducing errors and execution times. Different papers have recently presented the adoption of AR in maintenance: Ceruti et.al. [11] suggested the integration of AR technology for maintenance in aviation through the visualization of digital manuals; Said et.al. [12]

developed an AR-based assistance system for assembly tasks; Mourtzis et.al. [13] proposed IT platform able to connect the manufacturer with the field operator and provide AR procedures for remote maintenance; finally, Konstantinidis et.al. [14] presented an AR assistant for low-skilled operators to guide them in maintenance procedures via smartphones. All applications showed promising results on the AR adoption: reduction of execution time, errors, and related cost, and increase of the overall operation reliability as well as operators' capabilities. However, all papers focused on technological issues instead on user-related aspects.

Diversely, the advantages of adopting user-centric principles in designing and developing AR-based applications are numerous, as demonstrated by [15]. In particular:

- Increased user satisfaction and motivation, given by the greater user involvement;
- Improved product usability, resulting in improved UX and reduced errors;
- Improved productivity, thanks to more intuitive and easy-to-use interfaces and reduced learning time;
- Reduced costs, as direct consequence of reduced times and greater user satisfaction;
- Increased market competitiveness and brand reputation, thanks to the possibility to better meeting the users' demands.

Moreover, the adoption of a UX-driven approach requires creating a multi-functional design team and to be transdisciplinary, due to the strict collaboration of various business areas, such as marketing, design, production, and support [9]. The goal of this research is to blend the two worlds, namely the technological world and the user-related world, by focusing on the design of an AR user interface.

2. Research approach

The research adopted a so-called UX-driven approach, based on the analysis of the users' needs regardless of the tools used in the design phase and the type of product developed [16]. In this case, the "product" is represented by the AR application, so the proposed methodology is declined for AR application design. The proposed approach can be schematized in four phases as a cycle, as depicted in Fig.1. For each phase, specific sub-phases are specifically defined for AR interface design purpose.

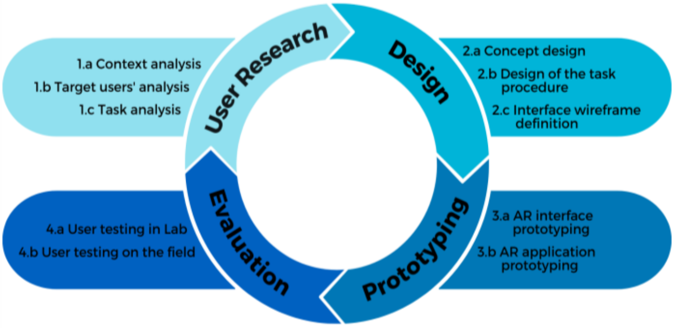

Figure 1: UX-driven cycle for AR application design.

As a cycle, each evaluation includes the assessment of the results against the initial user requirements and can include the design modification, as well as prototype development and evaluation phase. The cycle is repeated until the results are deemed satisfactory. The proposed method is general-purpose, but it was applied to the design and development of a smartphone-based AR application. The following paragraphs describe each phase in more detail.

2.1 User Research

The first phase consists of in-depth information research to define the design requirements dictated by the user, the environment in which the application is to be used, and the procedure to be performed. This phase includes three sub-phases: *1.a Context analysis, 1.b Target users' analysis and 1.c Task analysis.*

The context analysis is based on user observation on the field to collect important information about the working environment (e.g., available space, lighting, noise, machinery layout) and context-related information (e.g., industrial sector, standards to respect, possible risks and mitigation actions). The target users' analysis is carried out by both observing and interviewing users to understand their needs, skills, habits, and technological knowledge. In addition to this, it is possible to identify any difficulties they encounter while performing a specific task or, as in the use case addressed in the paper, why they are unable to perform several tasks independently. Finally, task analysis allows analyzing the entire procedure to be performed to understand the various tasks and to indicate, for each task, the actors involved, the timing, the tools adopted, and any specific requirements. Taking into consideration the AR technology, it may be necessary to break down the procedure into several steps, promoting a sequential flow instead of a group of multiple complex operations.

2.2 Design

In this phase, various design solutions are defined from the requirements found in the User Research phase. Usually, it is crucial to include all the requirements detected in the previous phase in each design solution. Then, the different design proposals are evaluated, and the best variant is carried forward to the prototyping phase. This phase includes: *2.a Concept design, 2.b Design of the task procedure and 2.c Interface wireframe definition.*

The concept design aims at defining several design alternatives capable of solving the problem addressed and choosing the best solution. In this phase, it is crucial to take into consideration the constraints and requirements posed by AR technology, which heavily influence the interface architecture, graphics, and the user interactions. Despite the software used for the app creation strongly affects the architecture of the app itself, it is basically rebuilt using the same targets and virtual objects, to generate the same interaction path, and consequently UX. Subsequently, the design of the task procedure is based on the previous task analysis, when the tasks identified are decomposed and adapted according to the users' need and the constraints imposed by the AR technology. Consideration must be given to the targets used in the application and the amount of information to be provided in each step of the procedure. Finally, the interface wireframe definition consists of a visual representation of the expected AR interface, where information is prioritized according to the design of the task procedure and the feature of the entire navigation system.

2.3 Prototyping

In this phase, the AR app interface is prototyped based on the concept and the wireframe developed in the previous phase. This phase includes: *3.a AR interface prototyping, 3.b AR application prototyping*. In the 3.a phase, the designed interface is prototyped including visual aspects and interaction behaviors by proper software tools (e.g., Adobe XD [17]). In particular, dimensions and shapes of buttons, icons, and text fonts are defined. After that, the application is realized by a proper AR software platform (e.g., Unity 3D [18]). First of all, the interface is developed according to the prototype, then the information architecture is implemented, and the digital contents are added. Finally, the application is built for the selected device.

2.4 Evaluation

The evaluation process involves generic users and experts to validate the prototypes. This phase generally includes: *4.a User testing in Lab, 4.b User testing on the field*. The aim of the 4.a phase is to test the developed app with users from different fields of expertise in a controlled environment. This test allows to detect the macro-problems of usability, not identified during the development phase, and to find out technical anomalies through a general and large sample of users. Subsequently, the 4.b phase allows testing the app in the real context of use, involving operators from the field, to assess the app usage in the real context of application and understand the users' real behavior to evaluate the quality of the realized user experience. An evaluation questionnaire is usually administrated after the test to collect demographic data and subjective assessment about specific aspects.

3. Industrial use case

The study focused on resolving downtimes of a CNC machine, due to the workpiece carrier pallet error. Up to now, a skilled worker from an external maintenance company must intervene to restore the machinery properly; indeed, internal maintenance operators do not have sufficient skills to perform the recovery. The research focused on the design of an AR application able to guide the local maintenance operators through the most proper procedure without any external support. The selected procedure was not too complex, to prove the validity of the AR support as a proof of concept, without dealing with long procedures. However, despite the limited duration in time, the selected procedure includes the main steps of numerous, more complex maintenance procedures. The following paragraphs describe the main phases of the proposed methodology as applied to the use case, as depicted in Fig.1.

3.1 User Research

For the *Context analysis* phase, a factory inspection was carried out to extract useful information from the working environment in which the application will be used. It emerged that the context of interaction is very noisy and mostly illuminated by natural light, if possible. After that, *Target users' analysis* was performed through user observation and operators' interview: we found that the workspace is included in the machinery cavity and is limited, about one meter wide, and the Maintenance Operator is not aware of the procedure to be performed. Such analysis allows us to define the limited dimensions of the assisted device and the type of targets to trigger the AR application, and the need to create a detailed step-by-step guidance to support the operators. Moreover, the *Analysis of the procedure* was carried out via task and link analysis to understand the tasks the operator must execute and the operator's movements on the machines and on the dashboard (with his/her hands and fingers). So, the task is a recovery procedure in which the activities must necessarily be performed in the given order.

3.2 Design

From the user research phase, two different *Concept design*s were defined. The former used illustrative photos in the upper half of the screen by including explanatory text, buttons at the bottom to go forward/backward in the procedure, and 3D virtual elements to indicate on the machine which buttons to press. The latter included textual instructions at the top half of the screen, two buttons at the bottom for navigation, and finally 3D virtual elements to indicate on the machinery which buttons to press. Since it is of paramount importance for the operator to clearly see the overlay of the virtual element on the machinery, it was decided to opt for the second concept, which offers greater visibility and better communication clarity. It is assumed, therefore, that the operator is less likely to make mistakes than with the first solution. Moreover, since the procedure has to be performed on the machine dashboard, it is decided to use *Image Targets*, in particular QRs placed on the dashboard itself, to activate the AR app.

The *Design of the task procedure phase* mainly consisted of reworking the original procedure into a step-by-step guide based on the information acquired during the User Research. The basic idea was to use images (i.e., QR codes, which are easily recognized by the app) and place them on the machine interface to divide the work zone into three different areas. Whenever an operation is to be performed on an area, the user is requested to frame the QR code associated with that work zone. After the user confirms having correctly framed the QR code by clicking on the green button both the textual and virtual instruction is provided.

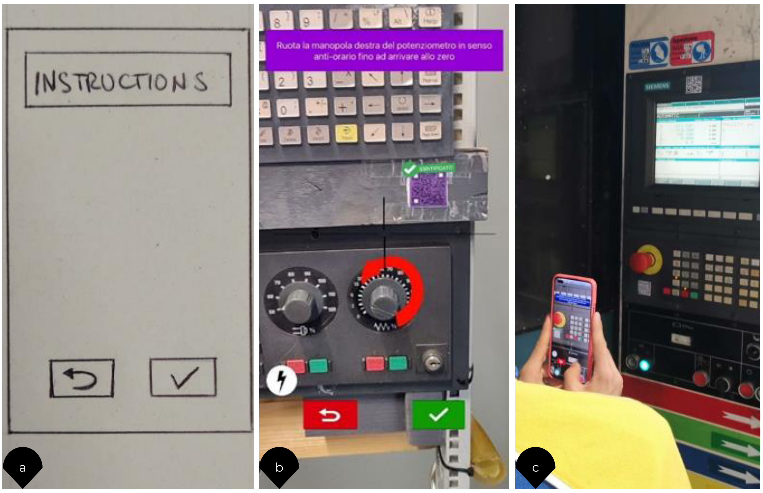

Figure 2: a) Paper-based wireframe of a generic procedure step, b) Example of the AR-supported reality (enhanced by virtual elements), c) On-field usage of the AR application.

Concerning the *Interface wireframe definition,* paper-based wireframes were realized to find the right solutions. The wireframe definition followed the need to maximize the communicative clarity and to practically guide the user step-by-step through the procedure, while minimizing the possibility of errors. A minimalist design with simple instructions was chosen in this case, with a rigid procedure to follow. As a result, the system offers limited freedom of navigation, but this choice was supported by the need to avoid errors and miss some steps. Indeed, the operator cannot have the ability to freely navigate the system, since each step must be performed successfully and in the right sequence for the machine to be restored. The "home page" contains two buttons: "start" to begin the procedure and "instructions" to get an overview of the application and its interface. In the procedure pages, three visual elements have been placed in the interface: the "instructions block" representing the area where textual instructions are provided, a “red button” (containing a back arrow) to return to the previous step, and a “green button” (containing a thick) to mark the conclusion of each step and proceed to the next one. Fig.2 shows an example of the interface as designed.

3.3 Prototyping

The *AR interface prototyping* was realized using Adobe XD to generate the graphical user interface and its interaction behaviors. Subsequently, the entire *AR application prototyping* was realized through the Unity 3D platform to create a high-fidelity prototype of the app, accessible from smartphones. The AR app development on Unity 3D was realized through *Canvas*, a *GameObject* that allows to create the application interface. We used a *Canvas* for each step of the procedure. Then the *Image Targets* were inserted using the *Vuforia Target Manager* and associated all the virtual elements to their respective targets. Next, *Canvases* were connected to each other through the buttons created in them, so the interaction was created, and the prototype of the application was complete.

3.4 Evaluation

The evaluation phase was composed of user testing both in Lab and in the field. In both cases, users were observed by experts without interfering during task execution and a dedicated questionnaires was administered after task execution. In both testing modalities, test was structured as a “Scenario Test”.

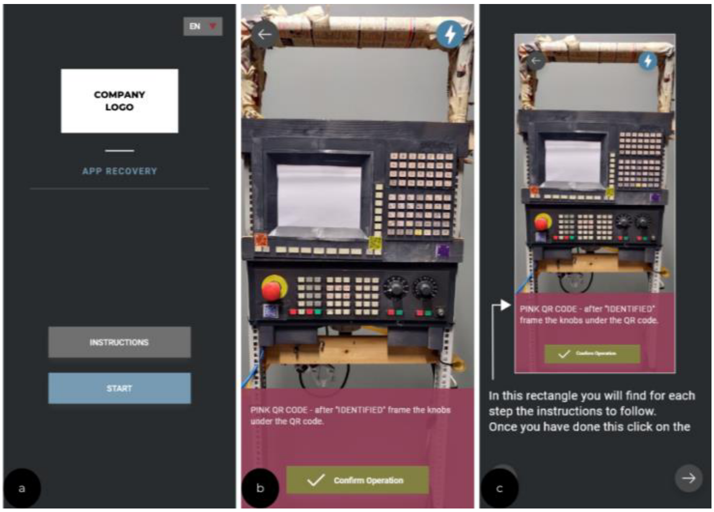

Figure 3: AR app prototypes for user testing in Lab: a) Homepage interface b) Example of a step in the procedure c) Example of a step in the instructions.

User testing in Lab was carried out using a 3D-printed reconstruction of the useful part of the CNC machine board, on which the maintenance procedure is carried out. 27 participants as generic users (77.8% male ; 22.2% female) ranged from 21 to 41 years old (aver. age of 26.56) and with different levels of familiarity with AR tools. Any of them was a maintenance technician, but all of them were graduated in technical areas (i.e., engineering). The feedback obtained during this phase highlighted the ease of use of the application thanks to the mutual presence of textual directions and clearly distinguishable virtual elements, guiding the users in easily completing the procedure. In addition, the interface was judged intuitive and clearly understandable also for users not familiar with AR. Fig.3 shows some examples of AR app interfaces during user testing in Lab.

User testing on the field was carried out to further optimize the system design. Two testing sessions were organized at the company premises. In the first session, 3 skilled workers (100% male, level of education based on high school diploma) were involved as target users. All of them were sufficiently familiar with the machinery, but only one of them previously used AR applications. In the second session, users were diverse from the first session, but still homogeneous (skilled workers, 100% male, level of education based on high school diploma). In this case, users went through a preliminary training phase in the use of AR. The first participant had a generic explanation of how the application works, the second participant had a more in-depth explanation of the application with an example on the first step to be performed, and the third participant watched the execution of the whole procedure by an AR expert.

3.5 Results and Discussion

The results collected on the field are reported in Table 1 (first session) and Table 2 (second session). Table 1 highlights the ease of use of the app and suggested that the user relied more on textual instructions than on virtual ones. In addition, the procedure was completed easier and faster by users with a prior knowledge about AR. Further optimization is being carried out according to the following aspects:

- Inserting an additional QR code to divide the working board into four different areas, more easily recognizable;
- Using colored QR codes to ensure that the correct zone is framed, associating the color of the QR code with the color of the related text block;
- Introducing an error signal when an incorrect QR code is framed.

Table 1. Results of the first session of *User testing on the field.*

ID	Gender	Age	Education Level	Previous Experience	No. Errors	Time (min)	Subjective Feedback
1	Male	28	High-school diploma	No	3	4:14	Need a preliminary training phase
2	Male	43	High-school diploma	No	4	4:36	Need an error signal for the wrong QR scanned
3	Male	55	High-school diploma	Yes	3	3:38	Add a QR code to improve usability

From the second session of *User testing on the field* results (Table 2), we can say that the training phase directly influenced the user performance: in fact, each operator reported a different degree of difficulty. In addition, from the user observation, a different level of errors committed was found (i.e., users with a lower experience on AR performed some tasks incorrectly, users with a better experience on AR completed the tasks without any errors). As a result, we can say that the familiarity of AR was crucial in determining the task completion, and the training phase assumed a very important role.

Table 2. Results of the second session of *User testing on the field*.

ID	Gender	Age	Education Level	Training phase	No. Errors	Time (min)
4	Male	29	High-school diploma	General explanation	2	2:57
5	Male	37	High-school diploma	In-depth explanation	1	2:29
6	Male	41	High-school diploma	AR-expert guided	0	2:03

Compared with the recent literature, the present research confirmed the importance of the training phase to achieve better performance using AR. However, the results demonstrated that the UX-driven approach significantly helps to design an intuitive and easy-to-use interface, able to drive the users into the correct interaction with AR and drastically reduce errors. Diversely to previous works, the proposed methodology pays attention to evaluating the users' performance and emphasizes the centrality of the user by involving people from the early design stages to better understand the potential problems and make the AR app very easy to learn and to use.

4. Conclusions

The paper proposed a transdisciplinary UX-driven methodology to design highly usable AR applications, with a particular attention to the user interface, promoting a human-centric view instead of a traditional technology-centric view. The results obtained from an industrial use case highlighted how AR can effectively support users in the proper execution of an unknown maintenance procedure without making mistakes, demonstrated the great potential of AR technologies in supporting workers in executing complex tasks. At the same time, the study highlighted the positive impact of a preliminary training phase on the user performance. In any case, the effort needed for training is limited since the skills necessary to correctly use the AR application are very basic. From a theoretical point of view, the paper showed how a TE approach, based on systems thinking and collaborative design practices, is useful to solve complex socio-technical issues, like manufacturing operations. From a practical point of view, the research demonstrated how AR can represent a novel user interface to provide on-time assistance and up-skill unexpert operators on the field, and to significantly reduce maintenance time and related costs. The limitations of the study mainly refer to: the limited number of participants involved in the on-field study, due to company restrictions, and the lack of data about the time of execution, before the AR-supported procedures, to have a detailed cost-benefits analysis. Future works will be oriented to extend the experimental study to more participants with different levels of knowledge and competences, and to validate the app on more complex procedures and different explanatory models. Moreover, a cost-benefits analysis will be added, considering also the current cost related to the maintenance procedures and the cost saving related to the AR-supported faster and safer procedures.

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