24th IMEKO TC4 International Symposium
22nd International Workshop on ADC and DAC Modelling and Testing
IMEKO TC-4 2020
Palermo, Italy, September 14-16, 2020

Reliability measurements of an Augmented Reality-based 4.0 system for supporting workmen in handmade assembly

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***Abstract* – The 4.0 paradigm has diffused across many sectors in a number of technological application fields, from industry to healthcare and constructions, and also to immaterial contexts, such as social events. The relevant enabling technologies of this paradigm are declined to adhere to the requirements of the specific field.**
Because 4.0 is often associated with technological advancement, in the literature, little attention has been dedicated to the adoption of 4.0 technologies in sectors that are not 'intrinsically technological'.
Starting from these considerations, the goal of this work is to address the possibility of extending the 4.0 Era paradigm also to fields that, by definition, are not technology-oriented, such as the craft sector.
In particular, as a case study, the adoption of augmented reality (AR) to administer instructions to a workman in the manual assembly of a product is addressed. In line with the 4.0 paradigm, a dedicated *workman-centered*, AR application was designed, implemented and tested. As a case study, the manual assembly of a mechanical clock was considered. After describing the design strategies and the implementation modalities, experimental tests were carried out to measure the reliability of the AR-based system.

I. INTRODUCTION

The current era is experiencing a large adoption of the 4.0 paradigm across a number of application fields (e.g., industry, healthcare, smart cities) [1, 2, 3, 4]. Recently, the 4.0 paradigm has also been extended to immaterial contexts, such as as the organization of social events [5]. In all these areas, the relevant 4.0 enabling technologies are generally tailored to suit the specific needs of the field. However, because 4.0 is often associated with technological advancement, in the literature, little attention has been dedicated to the adoption of 4.0 technologies in sectors that are not 'intrinsically technological' [6].

Starting from these considerations, the goal of this work is to address the possibility of extending the 4.0 Era paradigm also in fields that, by definition, are not technology-oriented, such as the craft sector. The goal is to introduce a methodology in which 4.0 industrial facilitators can be incorporated into the craft techniques.
In particular, as a case study, the adoption of augmented reality (AR) to provide instructions to a workman in the manual assembly of a product is addressed. AR technology has spread considerably, thanks to the ease of application and to the widespread use of hardware devices (mainly smartphones and tablets) able to support its adoption [7]. In the industrial field, there are several examples of the use of AR for improving manufacturing processes [8, 9, 10, 11, 12, 13]; however, at the state of the art, none has addressed the adoption of AR in handicraft.

In such a context, a dedicated AR application to provide AR instruction for manual-assembly of a product was designed, developed and tested. One of the requirements for the AR application is to be *workman-centered*, so as to ensure that the introduction of new technologies into a traditional field could be as seamless as possible for the user. Thanks to the adoption of AR, young workmen can use AR to learn from their mentors and for learning more quickly procedures that are (and remain) anchored to traditions.
As a case study, the manual assembly of a mechanical clock was considered. After describing the design strategies and the implementation modalities, experimental tests were carried out to measure the robustness and reliability of the AR-based system.

The paper is organized as follows. In Section II, the used materials are described. Section III presents the details of the methods and the strategy for developing a 4.0 *workman-centered* AR application. Section IV reports the results of the experimental tests for validating the reliability of the application. Finally, in Section V, conclusions are drawn and the future work is outlined.

Fig. 1. Picture of the mechanical alarm clock used for the case study.

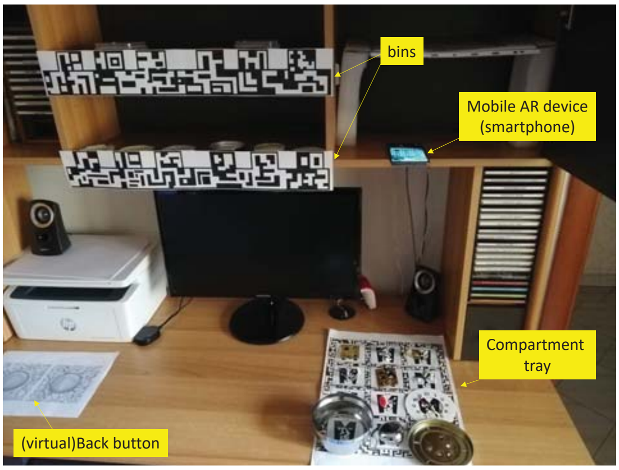

Fig. 2. Picture of the setup.

II. MATERIALS

As a case study, the manual assembly of a mechanical alarm clock was considered. The assembled clock is shown in Fig. 1. The reason for choosing this clock for the case study is that this product is commercialized disassembled, with a booklet containing the assembly instructions (this clock, in fact, is mostly intended for amateurs). As a result, for this product, it was possible to identify a specific set of instructions to be transferred into AR.

Figure 2 shows a picture of how the 'assembly station' was organized. In setting up the working environment, some working modalities were borrowed from the industrial field, to incorporate them into the application.
The basic product-specific components of the clock are contained in the compartments of a compartment tray. Other generic parts to be used for the assembly (such as screws or springs) are contained in bins on the shelf before the workman.

Fig. 3. Picture of the Epson Moverio BT350 AR glasses.

As explained later on in this paper, two AR applications were developed to administer the AR instructions. The AR applications were developed under Unity3d environment. Unity3d was chosen because of its versatility in the development of Android applications and for the perfect integration with the Vuforia AR tool.

Each application runs on an Android-based AR device. The first AR device was a set of optical see-though glasses, EPSON Moverio BT-350, shown in Fig. 3. These AR glasses are relatively low-cost and therefore suitable also for small-scale workmen's businesses. The BT-350 is equipped with a camera that records the scene in front of the operator, and allows the interaction of the application with the AR content.

The second AR device was an Android smartphone (Samsung A3). As can be seen from Fig. 2, the smartphone is mounted so that its camera always looks at the compartment tray. The reason is explained in the following section.
The applications on the two devices communicate and interact with each other via bluetooth.

The assembly instructions administered through the AR glasses were created by using pictures of the different phases of the assembly procedure.

III. METHODS

In this section, the major requirements and the design strategies for the AR applications are described in detail. Although they are presented in relation to a specific case-study, the considerations have general validity for *4.0 workman-centered* application fields.

A Split AR Applications

As aforementioned, to automate the use of the AR system and to improve its usability, two separate but mutually interacting AR applications were developed.
The reason for this design choice is that, similarly to an actual assembly line, the workman should keep the product

that is being assembled before him, while the compartment tray is on his side (as shown in Fig. 2). To avoid the need for the workman to constantly move his head to pick the component. In this way, it is enough for the workman to pick a component from the tray, that the AR application on the smartphone will identify the action and will communicate to the AR glasses to show the relevant instructions.

B Automation of the application for limiting human interactions

The first requirement for the AR applications was to limit the necessity of interaction between the operator and the AR system, so that the operator can use the AR applications hands-free. For this reason, the applications were designed so that they would proceed automatically, as the assembly procedure unfolds.
To automate the AR application, the first issue to address was to automate the action in which a component is taken from a compartment of the tray. Each compartment of the tray contains only one part or, at most, multiple parts to be picked at the same time. A very common problem is that the assembly part may be of any shape, dimensions and material; therefore, it is practically impossible to place AR markers on them. To circumvent this problem, in this work, a different strategy was implemented. Rather than recognizing the component itself and when the component is taken, the application was designed in order to automatically

To let the applications follow the workman actions, Vuforia's virtual buttons were used as shown in Fig. 4. Basically, the virtual buttons were used to specify areas of the frame marker that can interact with the user. When the workman's hand approaches the n^{th} cavity of the tray, the corresponding virtual button is clicked. As a result, an input is automatically sent to the smartphone application. In turn, the smartphone application sends a command to the AR glasses application and a dedicated code script that updates the assembly instructions is executed.
Virtual buttons can only have a rectangular shape, so to surround a cavity, several virtual buttons that have the same associated code script are used. Figure 4 shows a picture of the three virtual buttons that surround the first compartment: clicking any of them will execute the same script portion.
In this way, the first important objective is guaranteed, namely to carry out a procedure that advances automatically in the assembly process and without the necessity of interaction with the operator.

C Making the application more robust towards mistakes

Another important aspect was to make the applications robust towards human errors. For example, if by accident the workman picks the parts from the wrong compartment,

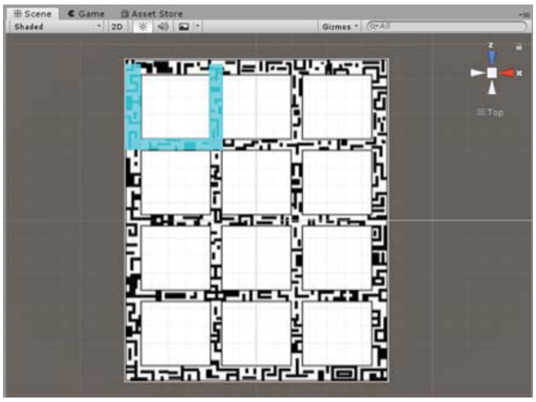

Fig. 4. Image of the design of the virtual buttons.

the application should be able to alert about this error. To this purpose, the following strategy was adopted.
Markers were placed also on the bottom of each cavity. For the considered case, a total of 12 compartments were considered. When the assembly has yet to be started, none of the 12 VuMarks is visible to the smartphone application, as they are covered with the assembly parts. Basically, the smartphone application was designed in order to identify which and how many VuMarks should be visible at any step of the procedure. If the operator picks a part from the wrong compartment, the underlying VuMarks will become visible to the smartphone app at the wrong instant. As a result, the application on the AR glasses will indicate that there has been an error in the procedure. While the assembly is carried out, the application is able to verify if the uncovered markers correspond to those expected in the sequence.

D Providing instructions on the assembly part contained in the bins

To complete the assembly, the workman has also to use components contained in the bins. Also this information is administered through the AR applications.
The adopted strategy was to apply a *strip marker* on the shelves of the bins. The application on the AR glasses was designed so that, for each step of the assembly procedure, when the workman looks at the bins, in addition to the assembly instructions, also yellow squares will appear. The yellow square appear in correspondence of the bins and indicate how many parts should be picked. Figure 5 shows an example of what the workman sees through his AR glasses during one step of the assembly procedure.

E Support functions: enlarging the images and the back button

So far, emphasis was given on the fact that the assembly procedure and the applications must proceed without direct intervention from the workman. However, there are

Fig. 5. Example of the images that appear on the AR glasses to the operator, when he looks at the bin.

Fig. 6. AR instruction displayed through the glasses. The virtual *back* button is also visible.

specific conditions in which it could be beneficial for the workman to have some limited interactions with the AR applications.
The first one is, for example, the possibility of enlarging the instruction images. In fact, in many AR glasses, the field of view is quite limited. Hence, instructions and/or AR images may appear relatively small to the operator, who may have difficulty in the correct interpretation. For this reason, one optimal strategy is that of allowing the workman to enlarge the image whenever it is needed. To this end, a square marker was added to the counter. Just by moving the gaze towards this square marker, the AR images will enlarge. This is expected to ease the burden on the workman.

Also, when assembly procedures are particularly complicated, it may occur that the workman makes a mistake. In this event, he should be able to go back on the instruction just as he could do with paper instructions. For this reason, the design of the application included an additional virtual button (Fig. 6). By looking at the marker, through the AR glasses, and passing the hand over the marker, the user can go back one step in the assembly procedure.

Fig. 7. Frame marker-based AR visualization indicating the compartment.

IV. EXPERIMENTAL TESTS FOR MEASURING THE RELIABILITY OF THE SYSTEM

A Description of the assembly workflow

The AR-assisted assembly workflow was as follows:

1. The workman picks the first assembly part from the compartment tray (Fig. 7). When he reaches for a component in the tray, the corresponding virtual button (Fig. 4) is activated.
2. The application on the smartphone detects this event; it recognizes the part that has been picked, and it communicates it to the application on the AR glasses.
3. Based on the received information, the AR glasses show the relevant instruction on how to assemble the component.
   The AR glasses application also shows information about which and how many parts should be picked from the bins, as shown in Fig. 5.

Once the first set of instructions has been carried out, the workman proceeds and picks another assembly part from the second compartment of the tray. This sequence is repeated for the successive parts; and the AR applications proceed automatically until the assembly is completed.

B Validation Tests and reliability measurements

To measure the reliability of the proposed AR-assisted assembly system, it was tested on a total of 10 persons. The subjects were asked to wear the Moverio BT-350 glasses and to proceed with the assembly of the alarm clock following the AR instructions.
The purpose of these experimental tests was to test the reliability of the software system against failures. In particular, the following application features were considered:

- correct hand detection in the tray compartment for the automatic instructions advancement;
- occurrence of undesired advancement of the instructions;

- correct hand detection in the tray compartment for instructions advancement
- correct detection of virtual key pressure for *pause*, *go back* and *restart* functions;
- correct detection of incorrect workman's behavior.

With regard to the first aspect, it was mentioned that when the workman places his hand in the tray, the instructions on the AR glasses should be updated simultaneously with the progress of the procedure. The clock assembly procedure is divided into 12 steps; therefore, the tray is made up of 12 compartments. To complete the assembly procedure, the workman will have to place his hand inside the compartment at least 12 times. As a result, theoretically, the 10 persons should have reached for the compartments a total of 120 times (12 times each person). However, during these tests, it occurred that the users needed to go back a few steps, so the number of insertions of the hand in the compartments was equal to 134. Of these, 18 insertions have failed at the first attempt: this means that the workman inserted his hand but the hand detection in the compartment was not immediate. Hence, he had to 'stimulate' again the system by reinserting the hand or insisting with the hand in the compartment.

As for the undesired advancement of the instructions, it sometimes happens that for light and/or shadow effects, the AR software that runs on the camera interprets a hand insertion in a non-existing compartment. This leads to an undesired progress of the procedure, and this forces the user to have to go back. This happened six times in total for the 10 repetitions.

In relation to the correct quad display on the bins, the assessment was made relying on a subjective statement made by the 10 persons at the end of the experiment. The question regarded the reliability of the visualized quad Four out of 10 subjects pointed out a non-perfect registration of the quads with respect to the bins, but still acceptable. The other six participants declared no such occurrence.

As for the responsiveness in the recognition of the markers and the appearance of the quads on the AR glasses, only one person complained of the slow response. He also pointed out that he had to move their head to find the right angle for the BT350 camera to find the right shot for the quads to appear.

With regard to the correct responsiveness to virtual key pressure, the following cases occurred: 14 cases of backward pressure; 10 cases of pressing the reset button; eight cases of pressing the play button after stopping due to incorrect behavior. Of these 32 total cases, 14 showed non-immediate reactivity to the pressure on the virtual button, forcing the operator to better frame the virtual button and to insist with the hand.

Table 1. Summarized results of the experimental validation

tested feature	**no. of tries**	**no. of failures**
hand detection in the tray compartment	134	14
undesired advancement of the instructions	134	6
correct quad display on the drawers of the counter	-	10
responsiveness in the recognition of the markers and the appearance of the quads	10 persons	1 complaint
correct responsiveness to virtual key pressure	32	14
detection of incorrect operator behavior	6	2

Finally, in relation to the correct detection of incorrect workman's behavior, it was verified that if the user picks up multiple alarm components simultaneously from the tray without following the sequence, an alarm is raised and the procedure automatically stops.For the purpose of the test, six participants were asked to intentionally pick more than one component from the tray at any step of the procedure. Only in four occasions, the alarm provided by the AR application was immediate. One participant, who behaved incorrectly in an advanced step of the assembly procedure (and therefore with more VuMarks uncovered) had to wait a few seconds before the incorrect behavior was actually identified as such. In practice, the greater the VuMarks discovered on the tray, the lower the reliability of recognition of incorrect behavior.

As for the sixth participant (always in an advanced situation of the procedure), no incorrect behaviour was detected: it was necessary to bring the camera closer to the VuMarks of the tray to recognize the incorrect behavior.

Finally, it should be noted that during the experiment, wrong behavior was reported twice when the procedure had been correctly followed, therefore it raised false positives.

Table 1 summarizes the results obtained for the validation of the different features of the AR applications. The obtained results show that, although there are some functionalities that need to be more robust, the overall AR applications successfully allow the completion of the assembly procedure. In particular, to improve the reliability of the system, the virtual keys function is the most critical. However, this is a function that is used only upon necessity; therefore, it does not compromise the overall performance of the AR-based system.

V. CONCLUSIONS

In this work, the possibility of extending the 4.0 Era paradigm also in the craft sector was addressed. In particular, a *user-centered* AR application was developed and implemented to assist (through AR-based instructions) the workman in a manual assembly task. The reliability of the developed AR system was tested through experiments on 10 persons who were asked to used the AR system to assemble a mechanical alarm clock. The obtained results showed that, in spite of some failures that occurred during the tests, the proposed AR-system is robust and effective in helping the user in carrying out the assembly.

Future work will be dedicated to further improve the reliability of the system. Also, thanks to the availability of systematic paper instructions for the considered clock, comparative experiments will be carried out by involving actual workmen and asking them to assemble the product either through paper or AR instructions. This will allow to assess possible difference in the learning curves of the subjects involved.

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