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Original
Augmented reality for the manufacturing industry: the case of an assembly assistant / Botto, Carola; Nematollahi Sarvestani, Amir; Cannavo', Alberto; Ricci, Paolo; Cappuccio, Daniele; Demarchi, Valentina; Morat, Giada; Saturnino, Alessandra. - STAMPA. - (2020), pp. 299-304. (Intervento presentato al convegno IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR 2020) - 6th Workshop on Everyday Virtual Reality (WEVR 2020) tenutosi a Atlanta, GA, USA nel March 22-26, 2020) [10.1109/VRW50115.2020.00068].

Availability:
This version is available at: 11583/2793358 since: 2020-12-24T12:59:27Z

Publisher:
IEEE

Published
DOI:10.1109/VRW50115.2020.00068

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(Article begins on next page)

12 September 2024

Augmented Reality for the Manufacturing Industry: The Case of an Assembly Assistant

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Abstract

This paper studies the impact of augmented reality (AR) on manual assembly operations in the manufacturing industry. A review of AR-based solutions in this field shows that assembly assistants capable to support the user in key activities (identification, handling, alignment, joining, adjustment and inspection) are particularly beneficial. Since assembly activities are generally not addressed within comprehensive solutions, an AR-based tool supporting all of them is proposed, and its effectiveness in terms of completion time and error rate is compared with the use of the corresponding paper-based instructions. Results of a user study unveil that the proposed tool generally reduces the number of errors, but the time needed to complete the assembly tends to increase. Limitations of the current solution and potential directions for future work are discussed.

Index Terms: Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Applied computing—Computer-aided manufacturing

1 Introduction

The widespread availability Augmented Reality (AR) technologies is attracting the interest of both practitioners and researchers in a growing number of fields, including education [14], computer animation [4], cultural heritage [7] and entertainment [10], to name a few. A very promising domain is represented by industrial applications [12, 13, 16, 20]. A number of works in the literature already recognized the great potential of AR to support key industrial activities like, e.g., training [2], (collaborative) design [26], repair & maintenance [9, 11], customer service [8], as well as assembly operations [19], to name a few.

With respect to the huge number of possible usage scenarios, this paper focuses on manufacturing, which promises to benefit more from the application of these technologies [3]. In particular, the work reported herein is aimed at investigating profitable applications of AR that could support the employees of a possible manufacturing company in performing their daily assembly tasks.

Many studies on AR-based assistance for manual assembly have been conducted already, proving the effectiveness of this technology in enhancing the user experience while increasing the number of correctly assembled products and improving operation speed [28]. A lot of attention was focused, in particular, on the latter metrics as they represent the two Key Performance Indicators (KPIs) for the business of the considered companies [31].

In this paper, a specific use case represented by precision manufacturing is addressed, although findings could be easily extended to other scenarios. Based on a review of relevant literature that is briefly summarized in Section 2, a list of features to be owned by a generic AR tool targeted to assembly operations were first identified. In this respect, it was found that integrating all of them in a single, comprehensive solution is not a common practice.

Thus, an AR-based assembly assistant tool was developed trying to effectively integrate all the identified assembly operations, while coping with the needs of a manufacturing company operating in the field of precision positioning systems. The design steps are illustrated in Section 3.1, whereas a prototype implementation and the expected usage workflow are described in Section 3.2 and Section 3.3, respectively. The effectiveness of the devised tool has been investigated through a user study, which is presented in Section 4. Results obtained are discussed in Section 5. Finally, the limitations of the current design and implementation, as well as possible future works are reported in Section 6.

2 Related Works

Works investigating the possibilities offered by the use of AR technologies as well as studies of its impact in the manufacturing industry are not new. An early example is represented by the system proposed in [23] more than twenty-five years ago. In this work, a see-through head-mounted display (HMD) was used to superimpose a computer-generated diagram on a specific position in the real environment to support human operations in aircraft manufacturing.

More recently, Nee at al. performed an extensive review of research activities carried out in the design and manufacturing domain considering AR applications [15]. In their work, they report in detail the current state of the hardware and software tools available for developing this kind of applications, by also discussing the associated technological challenges. Moreover, they provide examples of AR-based collaborative design, robot path planning, and assembly applications, among others, offering hints on emerging trends in these fields. A similar work by Lamberti et al. addressed the fields of AR-based maintenance and repair [11], which share many aspects with assembly operations.

As said, a review of relevant literature was performed in the present work with the aim to identify common aspects to be considered, in particular, in the development of an AR-based tool supporting the execution of assembly procedures. According to [17, 22, 30], the tasks characterizing assembly operations that could benefit more from the use of AR are the following:

- *identification* and *handling* of the needed components (i.e., which ones are actually needed, and how have to be manipulated);
- *alignment* of the components (i.e., which is the mutual position of two or more components, which are their contact surfaces, etc.);

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- *joining* of the components constituting the assembly (i.e., how do permanently attached or detachable components connect to each other);
- *adjustment* of the assembly's setting (i.e., refinement of the setting of a certain connection/component, e.g., to change the torque);
- *inspection* of the final result (i.e., assessment of the correctness of the assembly).

According to the findings of a comprehensive survey specifically focused on AR-based assembly applications [27], a significant number of works do not integrate the adjustment functionality, nor analyze the assembly status to recognize possible errors (inspection). They basically implement the so-called *step-based instructions* model, i.e., an approach to assembly operations that relies only on a combination of identification, handling, alignment, and joining. Moreover, a number of solutions still rely on text-based, 2D and/or static content to provide instructions [1,21,24], which could possibly limit the effectiveness of AR technology.

Taking into account the above considerations, this paper presents an AR-based tool which aims to comprehensively address all the mentioned assembly tasks while ensuring the effectiveness of provided instructions.

3 AR Assembly Assistant

This section illustrates the process followed for the design of the AR-based tool, by also describing in detail its components and its application to a possible use case.

3.1 Design Steps

A fundamental step in the development of the tool was the identification of the required features, since their interpretation and implementation can have a direct impact on how effectively the devised solution could assist the operators in their job. Descriptions and aims for all the feature are reported below.

- **Assembly status check**: involves the verification of the correctness of the assembly at the beginning and at the end of every step, considering the sub-assembly as both the output of a certain assembly step and the input for the next step. This approach, referred to as "poka-yoke" model [6], aims to prevent inadvertent errors, making the manufacturing process as much mistake-proof as possible.
- **3D interactive instructions**: it refers to the use of an animated exploded view of the assembly operation to be executed, with a 360° freedom of orientation of the explosion axis. It aims to provide self-explanatory, universal and adaptable instructions.
- **Additional contextual information**: consists in messages attached to a specific component, which are signaled by warning icons and provide additional cues for the correct execution of the current assembly step (e.g., quantity of needed glue, number of screwing turns, etc.). It aims to prevent mistakes due to the apparently secondary importance of the information: the need for glue, for instance, seems to be of primary importance, whereas its precise quantity is perceived as an unnecessary information, potentially overlooked when using common sense or long-term experience.
- **Flexible starting point**: consists in allowing the operator to start from a specific assembly step, ignoring the chronological order. It aims to ensure long-term relevance, since the complete assistance might result redundant once the employee gains expertise; conversely, he or she may always need support for a particularly complex assembly step, which should be selected directly.

Additionally, possible limitations or advantages related to the use of specific software and hardware solutions were considered.

With respect to software, based on current technology the AR-based visual recognition (the capability behind the assembly status check feature, and required for the identification of each individual component) can be accomplished with two alternative approaches: *object detection*, usually based on 2D image datasets, and *object tracking*, which makes use of 3D models of the parts to be recognized [25]. The object tracking approach was identified as preferable in this case, due to its potential for making the solution more scalable; in fact, generating a dataset for every part could be more time-consuming compared to the possibly automated acquisition of their already existing 3D models.

For what it concerns the hardware, despite the apparent advantages of AR applications based on HMDs in providing instructions always in the users' field of view and the possibility to let the operators use both hands, it seems that users feel more natural and intuitive the interaction with well-known tablet devices [18]. Moreover, the use of HMDs may have a negative impact on the cost of the developed solution, since suitable AR glasses are considerably more expensive than tablets devices. For these reasons, an approach based on a mobile – specifically, Android-based – app was chosen to implement the AR assembly assistant tool (although a HMD version may be envisioned as well).

Finally, the expertise of the precision manufacturing company was exploited to identify domain-specific requirements, which could nonetheless make the developed tool more interesting and effective also for other manufacturing companies. Results of this investigation can be summarized as follows:

- the majority of products in the precision manufacturing domain are assembled manually;
- there is a considerable amount of small and very similar components to be managed;
- growing worldwide presence (of this and other companies) implies issues related to geographical and linguistic distance;
- lack of possibly-needed clarifications (e.g., precise quantity of glue, number of turns, etc.) translates into a considerable lower number of correctly assembled parts.

3.2 Setup

The standard setup for the developed application is depicted in Figure 1. A video showing a user interacting with the AR assembly assistant tool is available for download at `https://bit.ly/36qUlJG`. In the following, more details about the hardware and software components will be provided.

3.2.1 Hardware

As said, the AR assembly assistant tool was developed for Android-compatible devices. The device selected for testing the prototype implementation is a Sony Xperia Z4 tablet equipped with a Qualcomm MSM8994 Snapdragon 810 CPU, an Adreno 430 GPU and a 1600×2560 10.1" display.

The tablet is mounted on an aluminum alloy arm through an holder mount clamp. Another clamp at the other hand of the arm allows it to be attached to the side of a work desk. While the standard position was thought to be set with the tablet screen parallel to the desk surface at a distance of approximately 25cm, the 360° adjustable structure allows each user to re-position the tablet at will.

Having identified the object tracking/recognition as a key function, in the implementation step it was decided to work with components whose features could specifically challenge this function. After some considerations (e.g., about using small components which are similar to each other, taking into account the presence of screws, supporting

Figure 1: Standard setup for the AR assembly assistant tool.

multiple configurations with the same components, etc.), the Meccano model construction system[1] was identified as compatible with the prototyping intent. In particular, a set of 10 component types (shown in Figure 1) were selected, strategically including similar ones (e.g., screws of slightly different sizes, 90° and 135° small joints, etc.) in order to stress, especially for testing purposes, the gap between eye-based and machine-assisted recognition.

3.2.2 Software

Among the available model-tracking software, the VisionLib[2] library [29] was chosen, and its functionality for 3D model-based tracking of a single component was extended to sub-assemblies recognition. Considering the working principle of VisionLib, 3D models of the selected Meccano parts and step-by-step sub-assemblies were created using the SolidWorks[3] CAD software. The VisionLib library was integrated in the main AR application, which was implemented using the Unity game engine[4]. The engine was exploited also to generate the 3D dynamic exploded views of the assembly steps based on the above models.

3.3 Usage Workflow

The developed AR-based tool envisages, as core functionalities, the component recognition, the assembly recognition, the 3D interactive instructions and the automatic tracking of the assembly step. The integration of key warnings and the flexible choice of the starting point are also included. Moreover, the tool has the following features: support for tracking sessions based on pre-configured groups of components (organized according to the sequential assembly steps); adjustable recognition order for a certain group of components; automatic transaction to the next step once the final sub-assembly has been tracked; different recognition configurations for the different component categories.

After the selection of the model to be assembled through a dedicated menu (Figure 2a), the application initiates the recognition of the components needed during the first step (Figure 2b). The panel on the left side of the interface contains the list of components, which are colored depending on their recognition status (red when they have not been recognized yet, yellow when attempting the recognition, and green when they have been recognized). The user is expected to recognize all the components before starting to assemble the model. He or she can select which component to start with by touching a red component in the panel, and can change the expected point of view for the recognition by dragging the virtual 3D model which is displayed in AR on the tablet's screen. In order to complete the recognition, the user should superimpose the right component on the 3D model until its outline becomes green (as depicted in Figure 2c). When present, warning icons near the components in the panel can be touched to show additional contextual information (Figure 2d).

When all the components have been recognized, a panel containing the 3D animated instructions for the current assembly step appears on the right side of the screen (Figure 2e). This panel can be opened or closed at any time by tapping its lateral label, whereas the animated model shown inside can be rotated with a drag gesture. The step ends with the recognition of the expected result of the assembly operation (Figure 2f), which is followed by the next step until the model has been completed. The users can freely navigate the steps by tapping on the arrows in the lower part of the screen.

4 User Study

This section illustrates the user study that was carried out in order to evaluate the effectiveness of the prototype implementation presented above. The study investigated the ability of the devised AR-based tool to provide the information needed for completing the assembly compared to a traditional process leveraging paper instructions.

4.1 Tasks

Since the functioning of the tool strongly relies on the identification of the components to be assembled and of the progression status, suitable model assemblies were identified and their relative instructions were created. Meccano parts were used, organized in two different assemblies later referred to as M_A and M_B (shown in Figure 3a and Figure 3b, respectively). The two models differ in the number of assembly steps (3 and 2 respectively), the number of different components (7 and 6 respectively), and the level of complexity (in terms of number of components involved in a single step). Differences between the two models were introduced in order to limit possible learning effects depending on the within-subjects approach chosen for the study.

The components needed to complete the two assemblies were placed on the desk together with additional, not necessary elements. During the experiments, participants were asked to assemble the two models using the AR-based tool (in the following referred to as *ART*) and the paper instructions (*PIN*). Participants were divided into two groups: the first group had to assemble model M_A using PIN and model M_B using ART; the second group used ART to assemble M_A and PIN for M_B. The tool to be used for M_A and M_B, as well as the tool to start with were randomly selected in order to limit biases and learning effects.

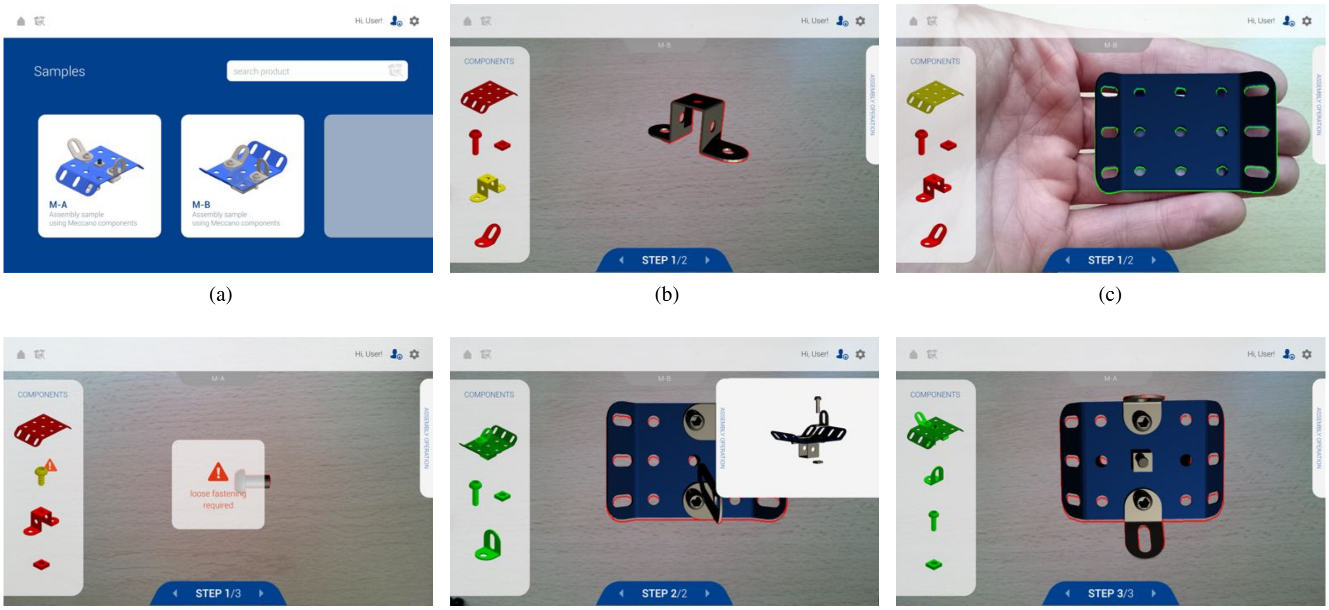
4.2 Participants

The study involved 26 volunteers (7 females and 19 males), encompassing students and academic staff from the authors' universities. Participants were characterized by different backgrounds and ages (between 20 and 65 years, with an average around 31 years). All the participants had already used a tablet; however, only a low percentage of them was familiar with AR applications and assembly operations. None of the participants was explained in advance how to use the application nor what they were supposed to assemble during the experiment.

4.3 Experimental Procedure

Each participant was introduced to a work environment relying on either the ART or the PIN (depending on the random choice made by the supervisor), together with the Meccano components. Afterwards, the participant was asked to assemble one of the two models by using the assigned method. Once completed the assigned task, the participant was invited to assemble the second model by following the instructions provided through the other method. During the

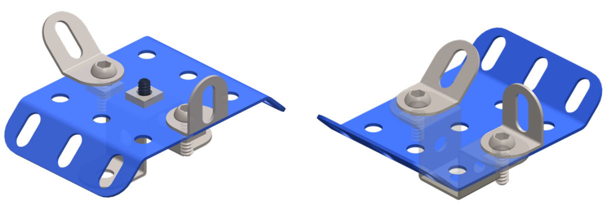
[1]Meccano: http://www.meccano.com/
[2]VisionLib: https://visionlib.com/
[3]SolidWorks:https://www.solidworks.com/
[4]Unity game engine: https://unity.com/



(a) (b) (c)

(d) (e) (f)

Figure 2: Interface of the AR assembly assistant tool: a) menu for selecting the model to be assembled b) component recognition, c) component being recognized, d) additional information related to the selected component, e) animated instructions, and f) assembly recognition.



(a) (b)

Figure 3: Assembly models used in the study: a) M_A, and b) M_B

experiment, no external support (e.g., about which component to pick) was given. Finally, each participant was asked to fill in a short after-test questionnaire.

4.4 Metrics

The evaluation included multiple metrics, encompassing the objective and subjective aspects reported below:

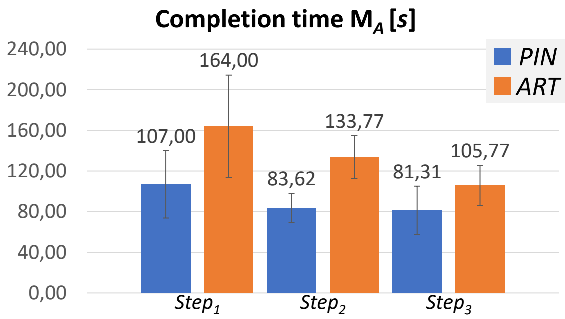
- *number of errors* made in the execution of the assembly procedure, which include both the choice of a wrong component as well as incorrect assembly operations;
- *number of errors in the final assembly*, corresponding to the wrong components in the finished assembly and to components not positioned as they were requested to be;
- *completion time* measured for each step;
- *perceived clarity and completeness* of the provided guidance;
- *possible interest* in the AR tool compared to paper instructions in case of long assembly procedures (tens of steps).

The last two metrics, which correspond to subjective measurements, were derived from questions presented in [5] and [30], and were evaluated on a 5-point Likert scale.

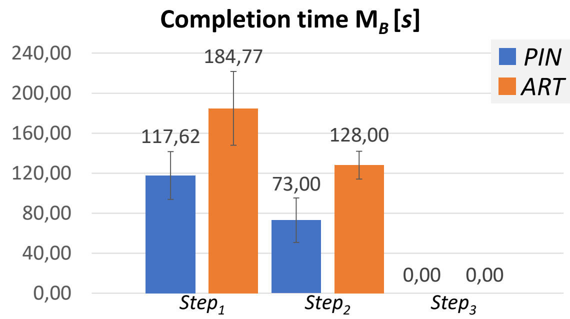
5 Results and Discussion

Results regarding completion time and number of errors are reported in Figure 4. It can be observed that differences between the two models did not impact on the results, as the numerical proportions for the metrics with the two models were preserved for ART and PIN. Based on this finding, it can be assumed that differences between the two models (introduced, as said, to limit learning effects) are due to differences between ART and PIN. In other words, models had no effects on the user study, and it would be possible not to consider them as factors to be investigated in the statistical analysis. However, for the sake of clarity, results will be presented and discussed separately for the two models. For each metric, statistical significance of differences between ART and PIN was evaluated using unpaired t-tests ($p \leq 0.05$). The differences between the two instruction methods for M_A (Figure 4a and Figure 4c) did not show any statistical significance, whereas the use of AR with M_B led to a reduction in the number of errors made in the assembly steps (Figure 4d): on average, participants made 1.38 and 0.92 errors with PIN in the first and second step, compared to 0.31 and 0.15 errors with the ART ($p = 0.0056$ and $p = 0.0158$), respectively. At the end of the assembly procedure, errors made with the ART were lower than with PIN (1.08 for PIN, 0.15 for ART, $p = 0.0497$). However, completion time (Figure 4b) increased in both the steps when participants used the ART (118s and 73s with PIN, compared to 185s and 128s with the ART for the two steps, $p = 0.0152$ and $p = 0.0016$).

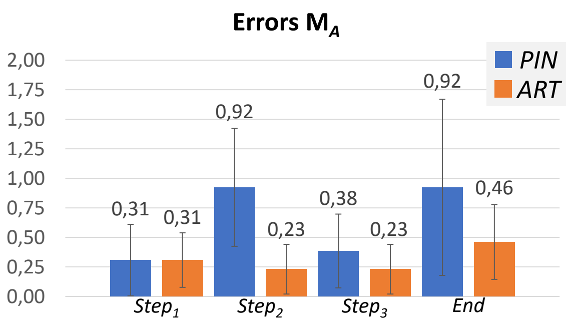
Subjective metrics were analyzed without considering the split in two groups. Guidance provided by the ART was judged as clearer and more complete than PIN (average score equal to 4.46 for the ART compared to 3.62 for PIN, $p = 0.0003$). Most of the participants declared that they would prefer to use the ART rather than PIN when dealing with a long assembly process (Figure 5). In particular, 30.77% and 42.31% of the participants expressed a high and a slight appreciation for the ART, respectively; 7.69% of them slightly preferred PIN, whereas the remaining 19.23% did not express any preference. None of the participants indicated a high preference for PIN.



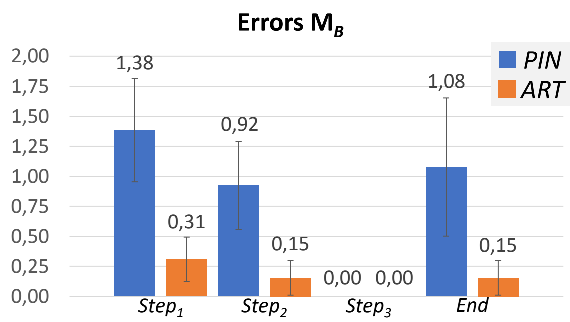
(a)



(b)



(c)



(d)

Figure 4: Objective measurements: a), b) completion time, and c), d) number of errors for M_A and M_B, respectively. Values are reported for each step. Values for "*End*" in c) and d) show the number of wrong components in the finished assembly.

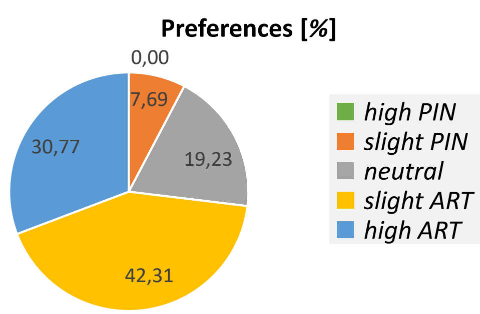


Figure 5: Percentages representing the interests in using ART and PIN in case of long assembly procedures.

The difference between the results obtained for the two models and, in particular, the lack of statistical significance for M_A could be due to the small sample size/number of participants considered in the study. Notwithstanding, results could also be due to differences in terms of the assembly complexity of the two models. In fact, the assembly procedure of M_A was expected to be longer than the other model, requiring slightly more complex manual operations; however, the assembly of M_B could lead to a higher number of errors because its steps involve a larger number of components to be handled together and, thus, to more things to keep in mind at once.

Based on obtained results, the ART appears to be an effective tool to reduce the overall number of errors. This reduction is paid with an increase in the completion time, which is mainly due to the component and assembly recognition phases (which are not explicitly performed when using PIN). The errors-time compromise offered by AR is apparently more relevant for operators when they have to deal with long tasks. It is worth remarking that these are the most realistic scenarios envisaged for the developed tool and the considered business.

Despite promising findings obtained in the experimental setup, the target manufacturing environment is expected to present important differences in terms of models involved, which are likely to be quite more complex; thus, operators' manual skills would be generally higher than those of volunteers involved in the experiments. The impact of these factors will need to be evaluated in further studies, by working with real assemblies and components, and involving (a representative number of) operators from manufacturing companies.

6 Conclusions and Future Work

This paper presented a prototype implementation of an AR-based tool that can be used in the manufacturing industry to support operators during assembly operations. A user study revealed that the devised application can reduce the number of errors made in the assembly operations at the cost of an increase in the overall completion time.

Feedback provided by the users at the end of the experiments highlighted a number of limitations of the current tool, which can be summarized as follows:

- the difference between the real component and its virtual model can greatly affect recognition performance, especially when the component is small and rich of details; for instance, in order to improve the recognition of screws, they were modeled without the threads, and the parameters of the VisionLib library were configured differently than for all the other parts.
- the light conditions are very critical, and a wrong position of the light sources can dramatically reduce the recognition rate;
- the camera of the tablet cannot detect occluded parts of the subassembly, nor determine the distance of the piece shown; this

could bring to the wrong recognition of a partially assembled model, or of a component which resembles a part of a bigger piece.

Future developments could be oriented to address the above issues and improve the AR-based tool. In particular, the (possibly automatic) optimization of the recognition parameters could be addressed. The possibility to adopt a position- and rotation-independent recognition method could be explored as well: this way, a component could be recognized by just placing it on the desk under the camera. Finally, an order-independent recognition approach could be implemented, so that to let the operator choose where to start the procedure from.

ACKNOWLEDGMENTS

This work resulted from a six-month R&D project commissioned and sponsored by Physik Instrumente (PI), a German leading manufacturer in precision positioning products, within the SEI Pioneer Programme framework, an Entrepreneurship & Innovation course on the development of an innovative deep-tech product starting from a challenge from a partner or institution, developed by School of Entrepreneurship & Innovation (SEI) and College des Ingenieurs Italia in partnership with Alta Scuola Politecnica. Activities were supported by the VR@POLITO initiative of Politecnico di Torino.

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