The International Journal of Advanced Manufacturing Technology (2021) 115:105–116
https://doi.org/10.1007/s00170-021-07049-8

ORIGINAL ARTICLE

Using augmented reality for industrial quality assurance: a shop floor user study

João Bernardo Alves[1] · Bernardo Marques[1] · Paulo Dias[1] · Beatriz Sousa Santos[1]

Received: 6 November 2020 / Accepted: 5 April 2021 / Published online: 3 May 2021

Abstract

Quality control procedures are essential in many industrial production pipelines. These repetitive and precise tasks are frequently complex, including several steps that must be performed correctly by different operators. To facilitate these, quality control tests are often documented with static media like video recordings, photos, or diagrams. However, the need for the operator to divide attention between the visual instructions and the task, and the lack of feedback lead to slow processes, with potential for improvement. By using augmented reality (AR), operators can focus on the task at hand while receiving visual feedback where it is needed. Nevertheless, existing prototypes are still at early stages, being tested only in laboratory conditions, far from mimicking real scenarios. The major contributions of this work are twofold: first, we present an AR-based quality control system capable of generating virtual content to guide operators by overlaying information in a video stream while performing real-time validation. The system evaluates the current status of the procedure to ensure the automatic progression to the next phase. Second, an evaluation was conducted in an industrial shop floor during 1 week, with seven operators to verify if the system was robust and understand possible efficiency gains when compared to the alternative, i.e., video instructions. Results showed that AR had a significant impact in procedures' execution time (reduction of 36%), while reducing the risk of human errors, which means AR technologies may represent a profitable and sustainable solution when applied to real-world industrial scenarios, in the long run.

Keywords Augmented reality · Industrial quality control · Shop floor procedures · Action verification · User study

1 Introduction

In today's digital world, the demand to deliver products at a faster rate and with better quality is continuously increasing. Industrial procedures present several challenges in quality control regarding, for example, product reliability improvement [20], predictive maintenance [19], human factors [14, 26], among others. As such, quality control procedures are gaining more and more importance in the industrial pipeline and there is a need to ensure that these procedures are performed quickly and efficiently, even more because failure to comply with clients' specifications may result in significant loss of time and money.

Currently, human factors have a crucial role in these procedures, which rely most of the time on specialized operators devoted to these inspection activities. In this context, distraction, fatigue, and lack of training, among others, may result in errors, which, in turn, can compromise task effectiveness [16].

Conventional quality control processes often resort to instructions available on paper or in digital format (e.g., photos, videos, or diagrams) to guide workers across different types of procedures. Typically, workers are required to map instructions to actions to be performed on real objects, without any feedback or additional assistance [32]. This lack of feedback can potentially lead to a slower process and error increase due to the divided attention between instructions and the task itself.

In this context, the use of information aid systems using augmented reality (AR) included as a component in the Industry 4.0 framework [10, 13] represents a technological opportunity [5, 31] as it may increase significantly task efficiency and reduce errors by keeping the worker focused on the task by providing visual feedback where it is needed [17]. AR allows to display digital information in context [4, 24] overlaid on top of the real world or a representation

✉ João Bernardo Alves
jbga@ua.pt

[1] IEETA, DETI, University of Aveiro, Campus Universitário de Santiago, Aveiro, Portugal

of it, being potentially useful for quality control processes with step-by-step instructions or other complementary data [23]. It may also reduce operation costs through an increase in spatial perception and a reduction in errors, time, and cognitive workload [7, 12, 18, 21, 23, 25]. By leveraging AR for quality assurance, companies can optimize the inspection process, thereby reducing time to market as well as waste. Specifically, by providing relevant information, AR tools can provide a guide to help workers navigate through unfamiliar scenarios or complex operations [6].

Despite all these potential advantages, ready-for-market AR tools are still scarce and as a consequence their actual benefit in real industrial contexts is not clearly demonstrated [22]. One possible explanation for the lack of AR use in industrial scenarios might be the difficulty to create virtual instructions: a tedious, task-dependent, time-consuming, and expensive process [27], being an active focus of research in AR maintenance applications [13]. Another possible reason for the few or little real case studies is the open-loop nature of most AR systems that only present information without providing any feedback or awareness about the current status of the assemble procedure [1]. This limitation of existing systems using AR leads to the lack of user action validation leaving to the user the decision if an action was well executed.

In this paper, we address both problems in a real industrial scenario, aiming to improve the efficiency of a specific quality control procedure. The paper describes an AR system developed to guide quality control tests based on two components: a tool able to create virtual position instructions based on human demonstration, and a real-time error detection algorithm to validate workers' actions during the process. A user study performed during 1 week in a real industrial scenario allowed to improve the original prototype developed in a laboratory and to evaluate the gains our solution can bring in an industrial shop floor.

The remainder of this paper is structured as follows: Section 2 presents related work about the use of AR in industrial quality scenarios. Section 3 describes the system developed to support the creation of virtual content and the algorithm used to validate his/her actions in a quality control procedure. Section 4 presents the user study, the experimental setup used, and the evaluation performed by real operators of the company. Section 5 discusses the results and impact of our method, and finally, Section 6 draws some conclusions and presents ideas for future work.

2 Augmented reality for quality verification in industrial scenarios

The growing number of recent papers on AR usage in industrial scenarios demonstrate that this technology has been gaining interest in the industry sector over time [8]. AR solutions are ultimately expected to be used in real industrial contexts [15] and, currently, many companies consider this technology important to provide new services related with their products [34]. Examining the work done since 2011 [13], the majority of the AR systems focused on assembly, while quality control is one of the least explored topics, as depicted in Fig. 1.

Regarding AR use in quality control, some works in the literature proposed early systems, although suffering from several limitations. Segovia et al. [30] developed a system able to display real-time reports essential for the decision making process with the objective of optimizing audit times. Franceschini et al. [16] developed a prototype to identify the products for inspection within a pallet with the objective of decreasing human errors. However, no trials have been conducted yet to assess if such a system would decrease the error rate or increase efficiency in that task.

Another example is using AR for quality control in the welding field. Despite automated robotic-based spot welding being the state of the art for body-in-white car manufacturing, the inspection of welding spots is still done manually to some extent [13], as the quality of spot welding on car bodies needs to be inspected frequently. Zhou et al. [33] tested a projector-based AR system for operators to easily identify welding spots that should be inspected. Doshi et al. [11] enhanced this system to improve the spot-welding quality during the manufacturing welding process, by highlighting spot-weld locations on vehicle panels for manual welding operators. Throughout 3 continuous months, their field experiments at an automotive plant showed at least a 15% increase in precision, decreasing the distance between the real weld-spot and the optimum position when

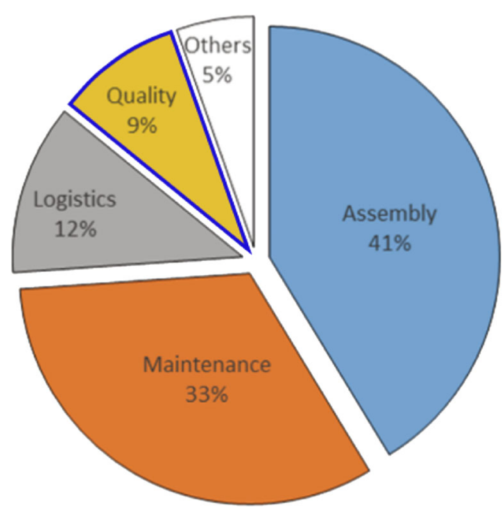

Fig. 1 Distribution of different fields of application for AR systems in industrial scenarios. From the ninety-six papers surveyed by [13], quality-related problems represents only 9%. Adapted from [13]

using the AR system. Antonelli et al. [3] used a similar technique to increase the accuracy and quality of manual spot welding in the process by indicating the relevant information as exact position of the welding spot, electric parameters to be adopted for every specific point, and quality of the welded spot. This system was only tested by a professional welder that was able to repeat the operation without errors after a short period of training.

It appears that quality control is an industrial field where AR researchers have not yet invested a significant effort leaving the use of AR in these scenarios relatively unexplored, despite the obvious benefits it can bring. Taking into consideration, the current relevance of the problem and the potential benefits of using AR to tackle it, as well as the scarcity of research concerning the topic, we argue that further research aiming the development of scalable AR-based solutions should be undertaken and this has been a motivation for our work.

3 Augmented reality-based system with validation for quality control

This section introduces the AR-system developed with an industrial partner to improve an existing quality control procedure used in the shop floor to check the error deviation in several key points of an automotive part. The developed method is expected to improve the existing procedure (relying on videos to illustrate the process) through AR by integrating two modules: the verification and the augmented creation methods. The AR part of the prototype creates the virtual instructions, and then overlays them on top of a live video stream to guide the user throughout the procedure indicating the location where to perform the next measurement. During the virtual information display, the verification algorithm determines if the operator is executing the procedure steps correctly at the predefined locations.

3.1 Case study scenario

The industrial task that motivates our work was raised by domain experts from the industrial sector, after a visit to the industrial plant in which they complained about the fallibility and lack of optimization of a quality control procedure they need to perform very often during the construction of a structural automotive part. The procedure consists in measuring deviation errors of an automotive part at specific positions and is an important specification of the clients resulting in much waste along the process (pieces that do not meet specifications are simply discarded). To fully understand the problem, a user-centered methodology was used and several meetings were held with domain experts. We also visited several times the shop floor having spoken with production line managers and operators who work specifically on that task to understand its nuances.

The procedure is performed with a wireless measurement device (a comparator) that is positioned manually by the employee at the specific locations to evaluate. Measurements are sent to an external computer and displayed in a monitor above the quality control cell. Figure 2 illustrates the environment where the process happens: the measurement device is in one of the predefined positions and the operator can check and validate (through the keyboard) the final measurement for the current part. As depicted in Fig. 3, after each of the nine measures, the operator needs to move away from the cell to verify that the measurements were effectively taken by looking to a display (see Fig. 4). This procedure is sequential since the operator must position the comparator in the next specific location after each measurement and trigger the new measurement using the keyboard.

A problem identified in the procedure described above was the time required to trigger the measurement since the operator had to move away from the supporting system to look at the monitor and then validate the measurement presented on the display before moving to the next action. This also requires the interaction with a wireless keyboard during the process (see Fig. 2).

3.2 AR visualization with user action validation

We developed a first version of a computer vision process in our previous work [2] to verify the correct localization of the comparator based on recorded data from a procedure performed under normal conditions. The objective was to trigger automatically the measurement when the device is correctly positioned and move automatically to the next stage showing the next location to be evaluated without any user interaction.

The correct localization of the comparator position is critical to trigger the measurement and enable a correct control of transitions between assembly stages. An algorithm based on a template matching approach to compare two 3D point clouds (one previously acquired with only objects that remain static during the procedure and the current point cloud under analysis) captured using the camera in the same pose in order to have an equal perspective was used for comparator location and validation of the its positioning. The algorithm starts by capturing a point cloud with the depth sensor (mounted in a way that provides a bird's eye view of the automotive part under test), as shown in Fig. 4. In a preliminary step, several point clouds were acquired to be used as a basis to build a new template that will be used to filter static objects in posterior stages. This template is obtained by adding all the point clouds, filtering it to obtain a 3D representation with 1-cm resolution (the main algorithm

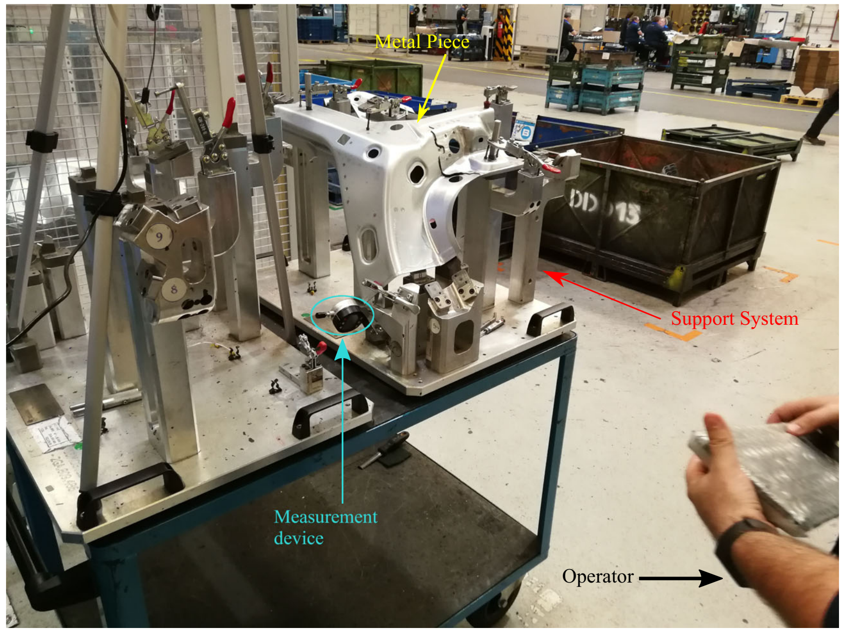

Fig. 2 Quality control process. A gauge ensures the correct placement of the automotive piece under evaluation. The measurement device determines the deviation errors at specific positions during the nine-step measurement process

parameters configured in this stage are presented in Table 1). Most of the objects presented in the point cloud are assumed to remain static during the procedure. The template is used to remove points outside a predefined working area. The original template is also used to cluster and detect moving objects that were not present during the initial configuration steps (such as the comparator in our example). Clusters with a number of 3D points below and above a specific threshold are discarded (see Table 1). The algorithm considers that the measurement device is located at a specific position if a cluster appears in the considered area in the same position for fifteen consecutive iterations (check Table 1 for tolerance values). The parameter values were obtained empirically using previously recorded bags of data and only fine tuning was necessary in situ to cope with variations such as different camera positions and orientations. This procedure is done during a calibration phase to minimize the occurrence of false positives previously to both the creation of AR content and the verification stage. The result of this process can be found in Fig. 5, where the white dots represent the point cloud regions that are equal to the initial template inside the working area while the red ones represent those which do not appear in the template. Figure 6 presents the workflow of the algorithm used in the generation of AR instructions and in the validation process. The difference between both modules resides in the fact that in the verification stage we already know what are the specific positions where the measurement device should be placed, while the AR module is position agnostic.

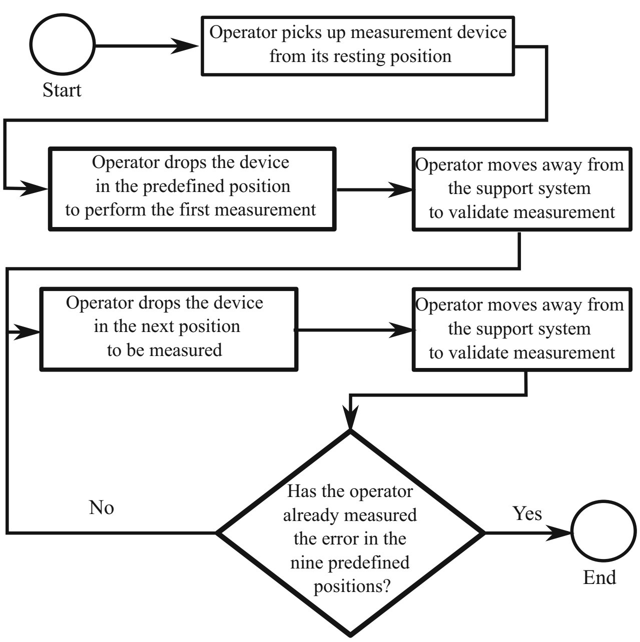

Fig. 3 Quality control process workflow. The procedure is composed of nine measures, and the operator needs to move away from the cell to verify each one of the measurements

The implementation uses C++ language due to the large variety of graphical and image processing libraries available, namely the ones that we use: ROS [28], OpenCV [9] and PCL [29]. The system runs on a laptop with an Intel i7-4710HQ processor and 8GB RAM.

3.2.1 Creation of AR content based on user demonstration and validation process

During the development of the prototype, we realized that the validation process can also be used to leverage the creation of virtual content based on human demonstration. For example, in Fig. 7, an operator placed the comparator

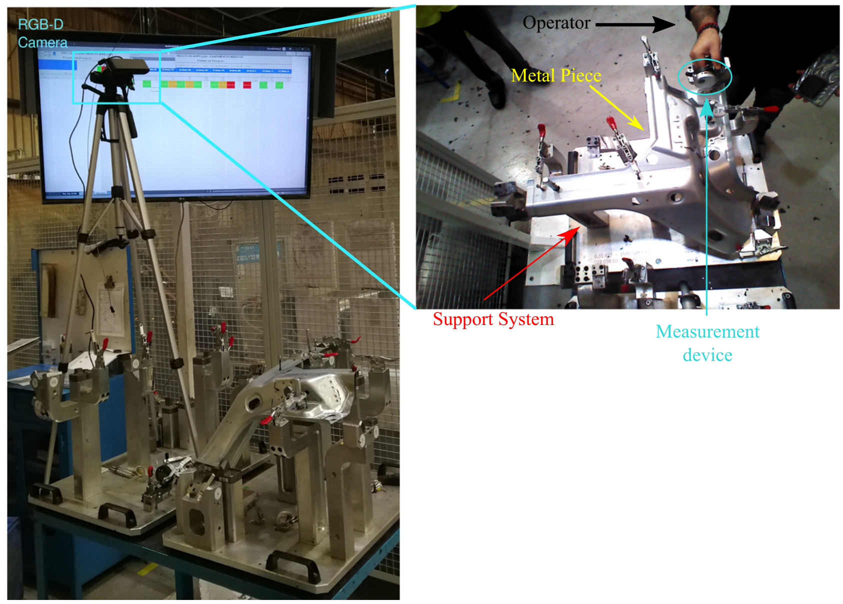

Fig. 4 Comparator positioning validation setup with a fixed depth camera held by a tripod looking down to the support platform used for quality control

in a given location and the system creates automatically the visuals (a green box in this case) indicating the device position detected. This makes the validation process useful not only to validate but also to help easily and quickly creating AR annotations for several situations.

The algorithm presented above also implies calibrating the camera used in terms of internal geometric and optical characteristics (intrinsic parameters) in order to reduce the distortion caused by the camera lenses and ensure a correct combination of the real and virtual objects. In this work, we use the standard chessboard calibration that relies on a pattern viewed in many different angles at different distances.

To create the AR content, we used the base algorithm to extract the 3D points already inside an individual cluster that is potentially correspondent to the measurement device. With these points and using the camera calibration, we obtain the pixel positions of each them determining the minimum and maximum image coordinates that will be used to build the bounding box indication the comparator position (green box in Fig. 7). After showing the desired instruction to the user, he/she is able to confirm if the instruction is well placed for a specific procedure step by placing an ArUco marker inside the camera field of view. Upon confirmation, the system stores the visual cue characteristics as well as the attributes of the points inside the cluster to be subsequently used in the verification process. This confirmation step is also a calibration step to determine the camera extrinsic parameters, as it stores the relative transformation between the RGB-D camera and the comparator in each procedure step.

Table 1 Parameters used in the algorithm designed to verify the measurement device position

Parameter	Parameter value
Number of point clouds to build initial template	10
Point cloud resolution in all dimensions	1 cm
Minimum number of points inside a cluster	10
Maximum number of points inside a cluster	100
Maximum distance between point cluster	1 cm
Distance tolerance from a cluster center to a specific position	5 cm
Number of consecutive iterations needed to validate the measurement device position	15

During the field tests in the industrial shop floor, it came out that only the visual marker in the video (green box) was not enough to convey the orientation the measurement device should have. Since our system is not yet able to infer the comparator orientation, an additional visual instruction was added manually for each step of the quality control test. A 3D model of the automotive part was enriched with a yellow 3D object representing the pose of the comparator for the specific step, as shown in Fig. 8. In the industrial case study, it is essential that this tool is accessible to users without knowledge about the system as it allows to re-calibrate it easily making possible the replication in another work station. This represents a matter of the uttermost importance because inside the shop floor there are industrial press machines working, which results in a non-neglectable impact on the remaining structures under the form of vibration. This vibration can cause the camera to move implying the execution of the calibration procedure every time it occurs. To determine if the calibration procedure

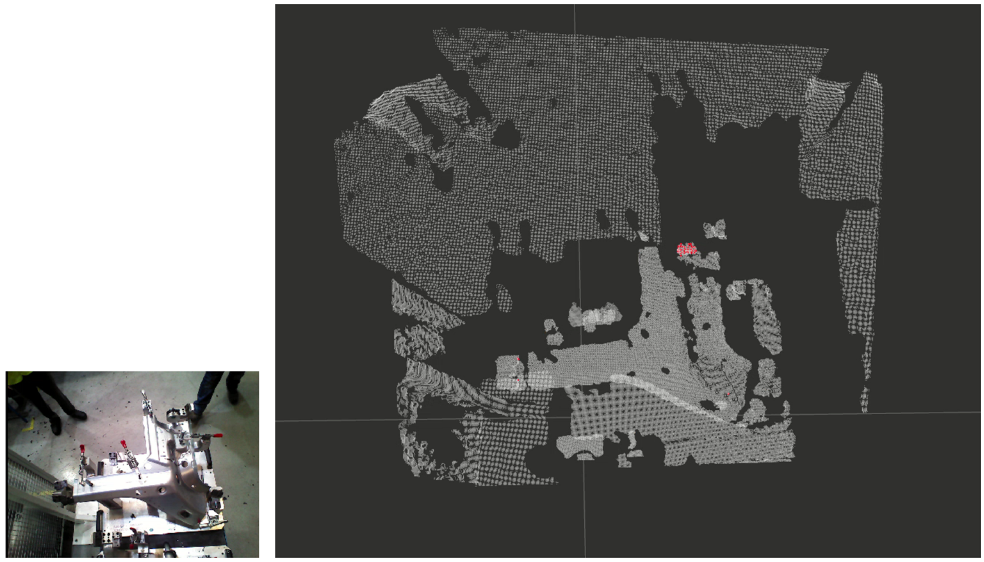

Fig. 5 Segmented point cloud after extracting only the objects that are not present in the initial template. On the left side, we have the RGB image captured by the camera corresponding to the captured point cloud shown on the right. On the right side, the white dots show the entire point cloud and the red dots correspond to regions that are not present in the initial template

needed to be executed, the point cloud template used in the beginning of the verification process is saved and compared with the one being currently captured.

The verification procedure takes place after the creation of AR content and is based on the algorithm described in Section 3.2—the AR creation process, but with a small improvement. Prior knowledge about point clusters attributes for each procedure step allows filtering most of the 3D information captured keeping only the relevant information for the step. This is essential to get a good resolution when comparing two point clouds while achieving real-time performance. The algorithm used is presented in Fig. 6, and the changes made to the base algorithm are highlighted in blue.

4 User study in an industrial scenario

A study was performed to compare the operator efficiency using two methods: the one currently used at the industrial partner (based on video instructions) and the AR system with validation developed in this work. The study was performed in a real shop floor scenario during 1 week with seven operators. Four had never performed the quality control test before (inexperienced users) while three perform this task routinely.

4.1 Experimental design

A within-subjects experimental design was used, meaning all users tested both conditions. The null hypothesis (H0) was that the two methods are equally usable and acceptable to perform the quality control procedure. The independent variable was the information guidance method provided to the operators with two levels corresponding to video vs AR conditions. Before the test, participants were instructed about how they should execute the task using both method by watching another user do the quality control procedure while a facilitator was explaining and answering questions about the process. The dependent variables were task performance and participants' opinion. To minimize learning effects during the experiment, the users were split into two groups and each group performed the conditions in different orders.

4.2 Experimental setup

To show the procedure steps to the operators, two different display methods were available: a large TV set playing an instructional video in the first method while the second one uses the same TV set to show a live video stream augmented with virtual instructions along with a 3D perspective of the examined object. The procedure instructions are shown on the same display in both methods but with a different perspective: the first presents the steps using a top-down bird's eye view and the second uses the RGB-D camera perspective and predefined perspectives to show the 3D instructions. Using these methods, the operators were required to complete the quality control procedure described in Section 3.1.

4.2.1 Instructional video method

The first method uses a non-AR method to display how the quality control procedure must be done by showing instructions on a television screen (see Fig. 9). In this condition, the operator uses specific keys of the keyboard to play and pause the video and to move between steps. This method was selected as it is a good approximation of the actions performed by the operators during the procedure currently used.

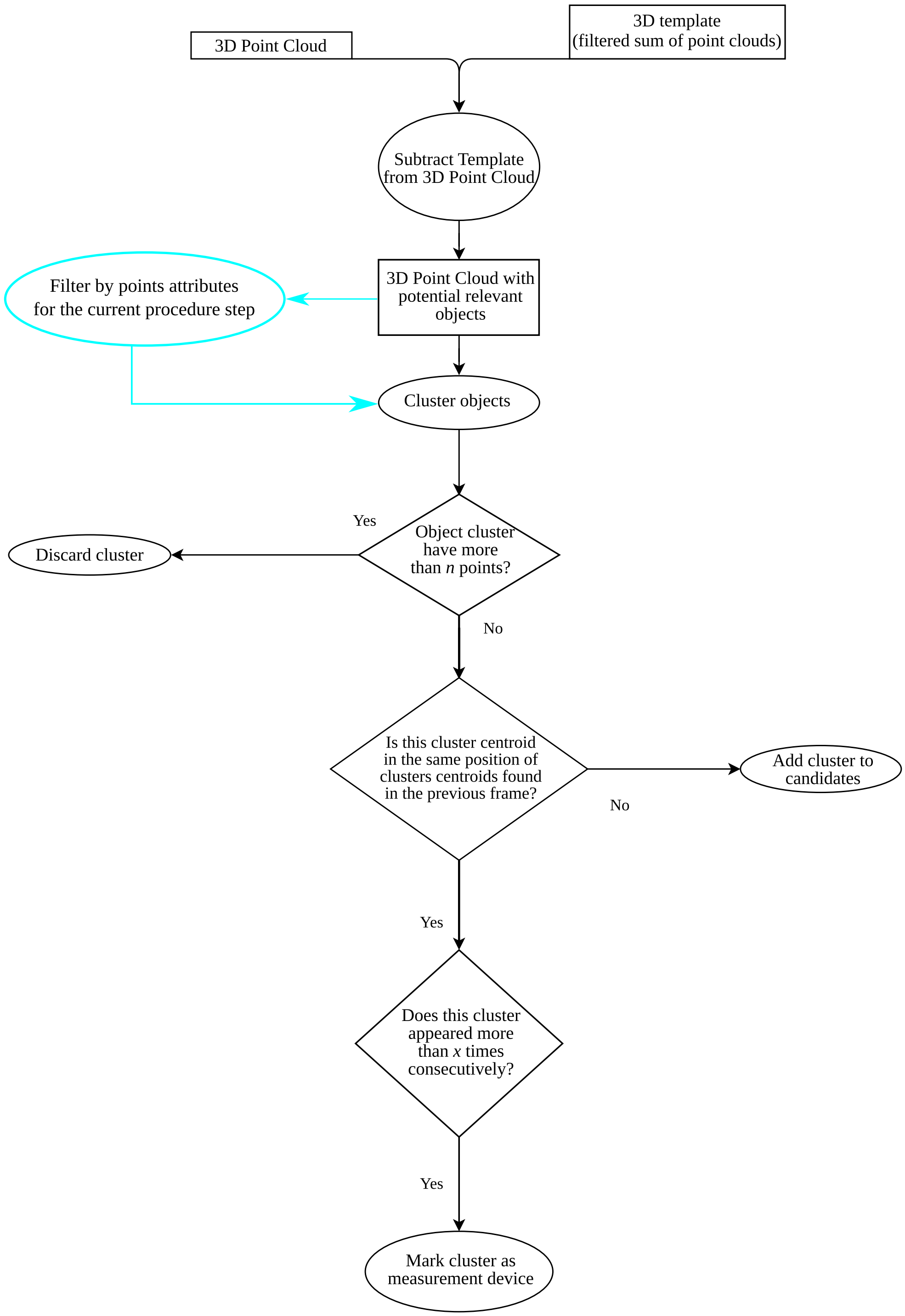

Fig. 6 Algorithm workflow aimed to perform the creation of virtual content for AR. The blue path corresponds to further improvements present in the user action verification algorithm described at the end of in Section 3.2.1

4.2.2 AR-Based method

The second method uses a specific setup, in which a camera is mounted on a tripod, pointing downwards at the gauge where the test takes place, which represents a way to have the system operational in a very short time period. The setup includes the same screen used before, but it augments the RGB-D live video stream by overlaying green boxes at the correct position for the comparator in each step (see Fig. 10). Instead of showing the instructional video, the augmented video is presented on the TV set alongside an image, as depicted in Fig. 11, containing a 3D model

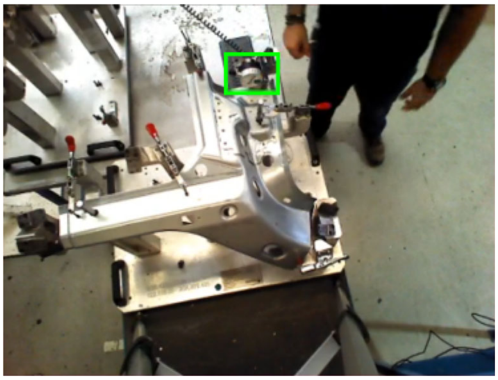

Fig. 7 Creation of AR content (green boxes) indicating where the device should be placed based on human demonstration

and a yellow marker indicating the pose of the comparator for the current step. In this method, the operator does not need to use the keyboard as the measure would be taken automatically when the comparator is detected in the correct position. The validation of the correct comparator positioning by the system is also used to automatically trigger the transition to the next assembly stage.

4.3 Measurements

Two types of measures were considered in this study: task performance and participants' opinion. Task performance is defined based on the task execution time (logged using the computer, measured in seconds). This measure is the time taken by the participants to complete all steps in the procedure. Participants' opinion was collected through post-task interviews based on a predefined set of questions. The questions asked were the following:

– Which was your favorite method?
– What are the main elements of that method that contributed for your choice?
– Which aspects can be improved?

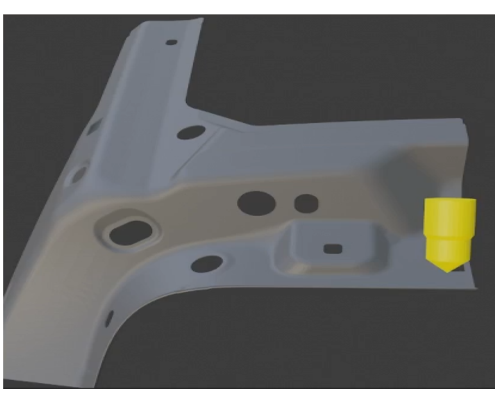

Fig. 8 3D model and a yellow object indicating the pose of the comparator for the second step of the procure

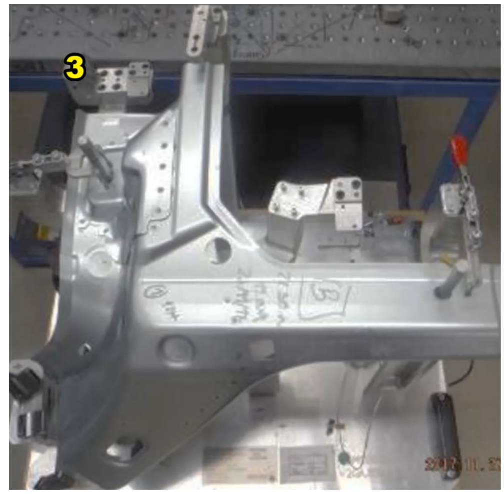

Fig. 9 Instructional video snapshot illustrating the proper position of the comparator (measurement device) for the quality control procedure third step—system in place in the partner before our proposal

4.4 Experimental procedure

As mentioned, all participants used the two experimental methods. Participants were instructed about the experimental setup and the tasks, and gave their informed consent. To avoid undesirable external factors as stress, participants were informed that we were interested in evaluating the system and not their performance. Participants were observed by an experimenter while performing the tasks. The observer also assisted them if they asked for help. Immediately after completing the task using the two methods, a short interview was conducted to collect participants' preferences, as well as other comments and suggestions.

5 Results and discussion

Table 2 presents the participants' execution time (in seconds) for all conditions as well as their level of expertise. The first obvious conclusion is the difference in execution

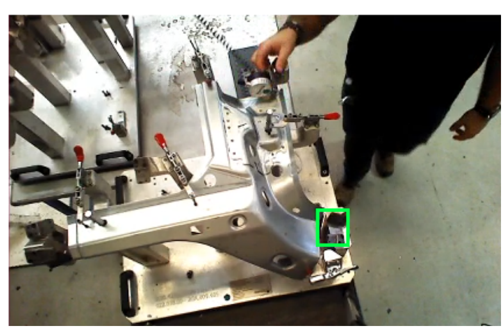

Fig. 10 Camera video stream augmented with green boxes showing the correct position for the comparator in each step

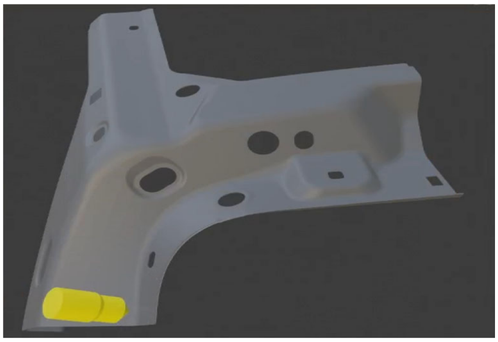

Fig. 11 3D model and a yellow object indicating the pose of the comparator for the third procedure step

time between the two methods: participants, independently of their expertise, performed faster using the AR-based method. The results also show that, with this method, inexperienced and experienced participants achieved a more similar performance (execution times range from 52 to 95 s against 78 to 193 s for the method using video instructions). As expected, experienced participants were faster in both conditions but the difference was smaller with the AR-based method showing that, with augmented reality, their performance was generally better than with video instructions. Moreover, as the difference between experienced and inexperienced participants was smaller with the AR-based method, results suggest that this method is more efficient to guide even users that have never performed the task before. Moreover, these results suggest that the AR-based method may decrease the learning curve of inexperienced operators implying savings in training programs. By carrying out the study with different user types (experienced and inexperienced), it allowed us to check if the system was robust enough to deal with unexpected behaviors and to assess the training potential of our solution. From the performed trials, we can state that the system performed well in both aspects.

Figure 12 shows the boxplots of the time required to complete the quality control procedure for each method.

Table 2 Procedure execution time using both methods and operator expertise

Execution time (s)		User expertise	Relative operation time reduction (percentage)
Video method	AR method		
120	70	Inexperienced	41.6%
193	95	Inexperienced	50.7%
112	81	Inexperienced	27.6%
105	66	Inexperienced	37.1%
83	69	Experienced	16.8%
78	52	Experienced	33.3%
101	54	Experienced	46.5%

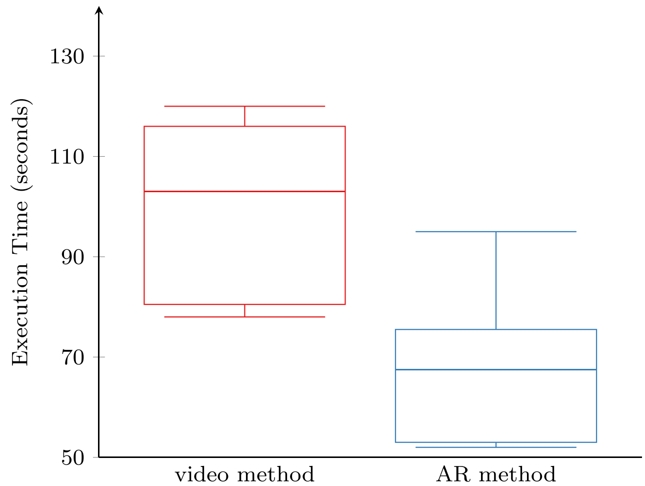

Fig. 12 Boxplots of the procedure execution times obtained with the two methods

It shows clearly that the AR-based method was able to speedup significantly the participants efficiency. Using AR, all the participants performed better and on average were 61.3% more efficient leading to a time reduction of 36.29% per operation. In a typical week, our industrial partner executes under normal conditions 756 procedures of this kind. Based on the results presented here, the AR-based system would allow 430 additional operations in the same amount of time, implying a significant financial gain. Another significant advantage of our system is its ability to automatically check if the operator placed the comparator in the correct location during the procedure. This functionality is of utmost interest since, according to the domain experts, operators often miss a position during the quality control due to boredom, tiredness, or lack of attention. Such errors result directly in financial penalties due to the delivery of defective parts to the final client, as well as extra waste.

Concerning participants' opinion, all operators preferred the AR-based method with the 3D model perspective, depicted in Fig. 11, instead of the instructional video. First, because it makes easier to understand where the comparator should be placed and provide instant feedback by moving automatically to the next step when the measurement is performed correctly. This preference could be related with the 3D content itself since the operators are used to work with 3D representations in their work environment. Some participants also mentioned that the augmented video stream complements the image using the 3D model as it provides real-time feedback being independent from the metal piece orientation in any situation.

Based on the 1-week field study, the prototype seems robust enough for real operation and also economically viable since, based on the average time reduction, it would allow an increase of 57% tests each week! Although the scope of the work presented do not aimed to assess economic viability, focusing mainly on system validation, it is also noteworthy that our industrial partner is interested in deploying the system in several gauges and other machines due to its potential benefits in terms of costs and efficiency and given its low-cost and easy setup.

6 Conclusion and future work

AR has been making its way into industrial scenarios and has shown great potential for several applications in scenarios as logistics, assembly, maintenance, and to a lower extent quality control.

In this paper, we presented an AR solution that shows its potential use in quality assurance procedures. The proposed AR system is composed of a virtual authoring tool that facilitates significantly the creation of step-by-step instructions based on user demonstration. In this context, we also present a visual verification algorithm capable of providing real-time feedback to an operator while conducting quality assurance procedures. We also described a user study conducted to compare the operator efficiency using two methods: video instructions—method that is currently used at the industrial partner and AR instructions based on the proposed AR system. This comparison was conducted in an industrial setup by operators working on the shop floor of our industrial partner, following a set of real quality assurance procedures. After a 1-week-long field study in a metal industry, results of a user study performed in the shop floor show that the system is capable of reducing significantly the execution time of a complex quality control procedure, allowing to increase by 57% the number of tests performed in a certain period of time. In the specific case addressed in this paper, this improvement could result in the execution of 440 more tests in 1 week. Besides presenting this advantage, our system also prevents users from making potential costly errors due to human inherent limitations as fatigue, distraction, and stress among others. Although not quantified in this work, these errors are prone to occur in peak production times due to the abnormal demands imposed on the operators could cost the company significant financial penalties, as well as waste. Overall, the study results suggest that the proposed system has the potential to improve KPIs such as the rate, count, and rejection rate, fundamental to improve the general efficacy of our industrial partner. The virtual authoring tool presented brings flexibility as it does not imply specialized knowledge, allowing defining in an intuitive way the procedure inspection positions, thus reducing costs in producing training materials. Moreover, the user study results suggest that the learning curve to train inexperienced operators using this approach is improved, resulting in extra savings in training programs.

To have a better understanding of the potential impact of our system, we also plan to extend the 1-week field study to a longer period of time, involving more participants and with a more professional setup (fixed structure in the gauge to avoid sensor movements and calibration errors). We plan to get an overview of how the industrial pipeline is structured by observing the operators' behavior (i.e., trajectories made to fetch and deliver pieces between pipeline stages) on the shop floor. After this observation, we intend to quantify how much time and motion is required to perform the processes related to the task. Then, we plan to measure how many pieces are verified using the previous methods and our AR-based method to obtain unbiased knowledge about the real gains for the task itself. This measurement shall be done in different time scales, to check how many pieces can be verified in an hour or during an 8-h shift. This will allow us to better understand the shop floor logistic dynamics. After these measurements, we plan to define the solution and deployment costs and evaluate its long-term financial impact, namely the payback period corresponding to the initial investment.

Also as future work, it would be valuable to use the image data for semantic extraction and not only to use it for visualization. This would make this system more robust and open the possibility of using it in other types of quality control scenarios. For example, knowing the position of a possible object of interest, it would be feasible and valuable to classify it as the expected object or not. This work can also serve as the base to create an AR visualization system capable of overlaying on the top of a real piece information about undesired offsets responsible for the quality check rejection, informing the operators where they should act to correct its defects. This would represent a major improvement in the production line since it would allow the reuse of a piece instead of leading to its disposal that occurs when the quality check failed. This would contribute to a leaner approach in several ways, by reducing time, waste, motion, and additional work.

Acknowledgements We want to thank the reviewers for their thoughtful suggestions for improving the earlier versions of this manuscript. We also thank everyone involved in discussion groups and case studies for their time and expertise, particularly Professor Carlos Ferreira from the University of Aveiro Department of Economics, Management, Industrial Engineering and Tourism (DEGEIT), for his constructive comments and suggestions, helping us improve our ongoing research. The present study was developed in the scope of Produtech – SIF – Solutions for the Industry of the Future [POCI-01- 0247-FEDER-024541]. This study was also supported by IEETA - Institute of Electronics and Informatics Engineering of Aveiro, funded by National Funds through the FCT - Foundation for Science and Technology, in the context of the project UID/CEC/00127/2019. The authors thank MCG and all the operators from this company that participated in this study for its collaboration and by the essential and relevant feedback given.

Author contribution Each author has substantially contributed to conducting the underlying research and drafting of this manuscript.

Funding Funding provided by Produtech – SIF –Solutions for the Industry of the Future [POCI-01- 0247-FEDER-024541] project.

Availability of data and material All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Ethical approval We confirm that this manuscript is original and has not been published, nor is it currently under consideration for publication elsewhere.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable

Conflict of interest The authors declare no competing interests.

References

1. Alves J, Marques B, Oliveira M, Araújo T, Dias P, Santos BS (2019) Comparing spatial and mobile augmented reality for guiding assembling procedures with task validation. In: 19th IEEE international conference on autonomous robot systems and competitions (ICARSC)
2. Alves J, Marques B, Dias P, Santos BS (2020) Using augmented reality and step by step verification in industrial quality control. In: Karwowski W, Ahram T, Etinger D, Tanković N, Taiar R (eds) Human systems engineering and design III. Springer International Publishing, Cham, pp 350–355
3. Antonelli D, Astanin S (2015) Enhancing the quality of manual spot welding through augmented reality assisted guidance. Procedia CIRP 33:556–561, 9th CIRP conference on intelligent computation in manufacturing engineering - CIRP ICME ’14
4. Azuma RT (1997) A survey of augmented reality. Teleoperators and Virtual Environments 6(4):355–385
5. Barata J, da Cunha PR (2021) Augmented product information: crafting physical-digital transparency strategies in the materials supply chain. Int J Adv Manuf Technol 112(7):2109–2121
6. Borsci S, Lawson G, Broome S (2015) Empirical evidence, evaluation criteria and challenges for the effectiveness of virtual and mixed reality tools for training operators of car service maintenance. Comput Ind 67:17–26
7. Bosch T, Könemann R, de Cock H, van Rhijn G (2017) The effects of projected versus display instructions on productivity, quality and workload in a simulated assembly task. In: Proceedings of the 10th international conference on pervasive technologies related to assistive environments, New York, NY, USA, PETRA ’17, p 412–415
8. Bottani E, Vignali G (2019) Augmented reality technology in the manufacturing industry: a review of the last decade. IISE Transactions 51(3):284–310
9. Bradski G (2000) The OpenCV Library. Dr Dobb’s Journal of Software Tools
10. Dafflon B, Moalla N, Ouzrout Y (2021) The challenges, approaches, and used techniques of cps for manufacturing in industry 4.0: a literature review. The International Journal of Advanced Manufacturing Technology
11. Doshi A, Smith RT, Thomas BH, Bouras C (2017) Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing. Int J Adv Manuf Technol 89(5):1279–1293
12. Dünser A, Billinghurst M (2011) Evaluating augmented reality systems. In: Furht B (ed) Handbook of augmented reality. Springer, New York, pp 289–307
13. Egger J, Masood T (2020) Augmented reality in support of intelligent manufacturing – a systematic literature review. Computers & Industrial Engineering 140:106195
14. Fang W, An Z (2020) A scalable wearable AR system for manual order picking based on warehouse floor-related navigation. Int J Adv Manuf Technol 109(7):2023–2037
15. Fite-Georgel P (2011) Is there a reality in industrial augmented reality? In: 2011 10th IEEE international symposium on mixed and augmented reality, pp 201–210
16. Franceschini F, Galetto M, Maisano D, Mastrogiacomo L (2016) Towards the use of augmented reality techniques for assisted acceptance sampling. Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture 230(10):1870–1884
17. Funk M, Kosch T, Greenwald SW, Schmidt A (2015) A benchmark for interactive augmented reality instructions for assembly tasks. In: Proceedings of the 14th international conference on mobile and ubiquitous multimedia, association for computing machinery, New York, NY, USA, MUM ’15, pp 253–257
18. Funk M, Kosch T, Schmidt A (2016) Interactive worker assistance: Comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions. In: Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing, ACM, New York, NY, USA, UbiComp ’16, pp 934–939
19. He Y, Gu C, Chen Z, Han X (2017) Integrated predictive maintenance strategy for manufacturing systems by combining quality control and mission reliability analysis. Int J Prod Res 55(19):5841–5862
20. He Y, Liu F, Cui J, Han X, Zhao Y, Chen Z, Zhou D, Zhang A (2019) Reliability-oriented design of integrated model of preventive maintenance and quality control policy with time-between-events control chart. Computers & Industrial Engineering 129:228–238
21. Henderson S, Feiner S (2011) Exploring the benefits of augmented reality documentation for maintenance and repair. IEEE Trans Vis Comput Graph 17(10):1355–1368
22. Jetter J, Eimecke J, Rese A (2018) Augmented reality tools for industrial applications: What are potential key performance indicators and who benefits? Comput Hum Behav 87:18–33
23. Khuong BM, Kiyokawa K, Miller A, La Viola JJ, Mashita T, Takemura H (2014) The effectiveness of an ar-based context-aware assembly support system in object assembly. In: 2014 IEEE Virtual Reality (VR), pp 57–62
24. Michalos G, Karagiannis P, Makris S, Tokçalar Ö, Chryssolouris G (2016) Augmented Reality (AR) applications for supporting human-robot interactive cooperation. Procedia CIRP 41:370–375
25. Neumann U, Majoros A (1998) Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance. In: Proceedings of the virtual reality annual international symposium, IEEE computer society, USA, VRAIS ’98, p 4

26. Peruzzini M, Grandi F, Cavallaro S, Pellicciari M (2020) Using virtual manufacturing to design human-centric factories: an industrial case. The international journal of advanced manufacturing technology
27. Plopski A, Fuvattanasilp V, Poldi J, Taketomi T, Sandor C, Kato H (2018) Efficient in-situ creation of augmented reality tutorials. In: 2018 workshop on metrology for industry 4.0 and IoT, pp 7–11
28. Quigley M, Conley K, Gerkey BP, Faust J, Foote T, Leibs J, Wheeler R, Ng A (2009) ROS: an open-source robot operating system
29. Rusu RB, Cousins S (2011) 3d is here: Point cloud library (pcl). In: 2011 IEEE international conference on robotics and automation, pp 1–4
30. Segovia D, Mendoza M, Mendoza E, González E (2015) Augmented reality as a tool for production and quality monitoring. Procedia Computer Science 75:291–300. International conference virtual and augmented reality in education
31. Shahin M, Chen FF, Bouzary H, Krishnaiyer K (2020) Integration of Lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises. Int J Adv Manuf Technol 107(5):2927–2936
32. Wu LC, Lin IC, Tsai MH (2016) Augmented reality instruction for object assembly based on markerless tracking. In: Proceedings of the 20th ACM SIGGRAPH symposium on interactive 3d graphics and games, association for computing machinery, New York, NY, USA, I3D ’16, pp 95–102
33. Zhou J, Lee I, Thomas B, Menassa R, Farrant A, Sansome A (2011) Applying spatial augmented reality to facilitate in-situ support for automotive spot welding inspection. In: Proceedings of the 10th international conference on virtual reality continuum and its applications in industry, association for computing machinery, New York, NY, USA, VRCAI ’11, p 195–200
34. Zubizarreta J, Aguinaga I, Amundarain A (2019) A framework for augmented reality guidance in industry. Int J Adv Manuf Technol 102(9):4095–4108