

An Augmented Reality inspection tool to support workers in Industry 4.0 environments

Abstract

Among the key technologies of Industry 4.0, Augmented Reality (AR) is one of the most promising and enabling technologies for supporting factory workers and engineers at the workplace. To this end, the paper proposes a novel AR tool to assist operators during the inspection activities for the detection of production and assembly errors. In fact, thanks to the superimposition of the 3D models, as designed by the technical office, a worker can easily detect the presence of design discrepancies on the final physical assembled product and report them by adding 3D annotations directly on virtual models.

This AR tool has been developed by using ARCore™ libraries to ensure, in the first place, its compatibility with commonly used devices for which workers are already trained and, secondly, to take advantage of the hybrid-tracking techniques that combine vision- and sensor-based methods to improve the reliability of the AR visualization. Nevertheless, the proposed AR tool adopts multiple markers to minimize tracking errors and therefore to provide greater freedom of movement to the user, who can use the tool also for the assessment of large-size products.

Field experimentations have been carried out on a real case study with end-users in order to assess its usability and perceived mental workload through the SUS (System Usability Scale) and NASA-TLX (Task Load Index) standard questionnaires, respectively. The usability study was performed taking into account also objective metrics, i.e., by analysing user performance in target acquisition tasks while interacting with the AR tool. Statistical analysis proved that the adoption of this AR tool requires low mental demand, and its usability has reached a high level of satisfaction both by the factory workers and engineers involved in the user study.

Keywords: Augmented Reality; Industry 4.0; Operator 4.0; Google ARCore; Marker-based tracking; Usability studies

1. Introduction

The advent of Industry 4.0 has led to the rise of new digital industrial technologies and to physical transformation of the industrial landscape through the integration of new tools and techniques which increase production efficiency, produce higher-quality goods, and reduce costs [1-4]. This technological transformation will have significant implications on the nature of work in industrial environments, since the new working environments will directly affect the operator by creating new interactions not only between humans and machines, but also between digital and physical worlds [5-8]. In this context, a worker becomes a smart and

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skilled operator whose human physical, sensorial, and cognitive capabilities are enhanced and augmented by new systems, machines, and tools that feature advanced human-machine interaction technologies [9].

Among the key enabling technologies of Industry 4.0, Augmented Reality (AR) is one of the most promising techniques for improving the transfer of information from the digital to the physical world of a smart operator in a non-intrusive way. Thanks to its capability to integrate virtual information into the user's perception of the real world, AR can actually support operators at their workplace, in real-time and during manual operations, by reducing human errors and the dependence on operator's memory, printed work instructions, and printed technical drawings which need to be interpreted beforehand by a skilled worker [8]. In fact, in the last years, various and different AR-based systems and tools have been developed by researchers for many manufacturing sectors to support operators, especially for assembly, training, maintenance, and inspection activities. Inspection typically involves a set of checks to be performed on real products, and in particular, it can concern the detection of design discrepancies between what was planned and what was built. The execution of this activity is therefore essential in the manufacturing process, and especially in the Oil&Gas sector where many factors such as the complexity of the products, the inability of the operator to comply with certain assembly sequences, and the occurrence of constraints and limitations not identified in the design phase, can potentially lead to mistakes or design changes during the production and assembly activities. Another critical aspect related to the inspection activities concerns the annotation and formalization of the detected errors and design changes, and the subsequent sharing of the information with the technical office. Thus, the inspection activities demand a great deal of concentration and a high mental workload [10] due to different reasons. First of all, the operator's attention should be shared between the physical prototype and the related design data while detecting potential errors. Second, this activity is usually carried out manually by operators with traditional paper-based instruments. Third, even though this task is usually performed by experts, it remains a subjective evaluation and the results depend on operator's capabilities and experience. As a consequence, all this might increase the difficulty rather than simplify the operations [11] and leads to a reduction in the efficiency of the user's processing capacity who is, therefore, more likely to make a mistake.

On the basis of these considerations, the paper proposes a novel AR tool intended for application in industrial inspection processes with a threefold goal: to assist operators at the workplace during the inspection activities for the detection of production and assembly errors; to require users low cognitive and physical workload in the execution of this activity; and to reach high usability perceived by users while adopting the proposed AR tool. In particular, thanks to the superimposition of the 3D models, as designed by the technical office, on the final physical assembled product, a worker can easily detect the presence of design discrepancies and report them by adding 3D annotations directly onto virtual models. In this way, both experts and novices to the inspection of products can adopt the proposed tool to detect errors without requiring high knowledge or ability to interpret manuals or technical drawings. This AR tool has been designed on the basis of experiments and prototypes previously developed and tested to better understand end-users' needs, conditions of use, and functionalities to be implemented [12,13]. Differently from the previous prototypes, this AR tool has been

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developed by using the Google ARCore™ SDK (Software Development Kit) [14] in order to ensure, firstly, its compatibility with commonly used devices, e.g., smartphones and tablets, for which workers are already trained and secondly, to take advantage of the hybrid-tracking techniques that combine vision- and sensor-based methods to improve the reliability of the AR visualization. However, from the previous experimentations carried out with end-users, it came out that the size of the real components can affect AR visualization. The influence of these factors is mainly due to the fact that the inertial sensors, adopted to implement the hybrid tracking technique, are affected by the drift error which is perceived by a user through the misalignment visualization of the virtual models on the real products. For this reason, the developed AR tool employs an automatic detection of multiple markers that allow for minimizing tracking errors and therefore for providing a greater freedom of movement to the user, who can use the tool also in case of large-size products.

Field experimentations have been carried out on a real case study with end-users in order to assess its usability and perceived mental workload through the SUS and NASA-TLX standard questionnaires, respectively. The usability study was performed taking into account also objective metrics, i.e., by analysing user performance in target acquisition tasks while interacting with the AR tool.

2. Related works

Although AR is considered a developing technology, with numerous barriers to its adoption in the industrial field caused by ergonomic and technical issues, its potential benefits are widely recognised [15,16]. AR, in fact, is a suitable method to support operators during their internal enterprise activities by sharing and disseminating expert knowledge, providing training, and prompting to make their work more efficient, hence reducing the number of errors due to inexperience, distraction or contextual limitations [17-24]. In particular, thanks to its capability to enhance operators' skills by providing contextualized data in the users' sightline via different technologies such as static screens, projectors, wearable and handheld devices, AR can play a crucial role in a variety of industrial application domains to support operators during assembly/disassembly [25-32], maintenance [33-44], training [45-49], and monitoring and inspection tasks.

Real-time monitoring of manufacturing processes can be benefited from AR that results in improvements in product quality, detection of machine failures, reduction of costs and time. AR functionalities are therefore combined with SCADA (Supervisory Control and Data Acquisition) systems thanks to which data gathered by sensors mounted on machines are augmented onto the real manufacturing environment. In this way, a comprehensive and intuitive perception of the real-time machining processes is provided to users. In this regard, Barreiro et. al [50] have pointed out as AR visualization devices can be helpful for monitoring the status of machinery by providing relevant information to users that use head-mounted display systems. Soete et al. [51] have combined traditional SCADA functionalities with those provided by AR that results in a monitor-based AR supervisory tool for a simulated automatic logistic process. Kranzer et. al [52] have proposed an intelligent maintenance planner based on AR technique to guide operators during maintenance

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activities. Olwal et. al. [53] have developed an autostereoscopic optical see-through spatial AR system. It integrates a transparent holographic optical element mounted on the machine's safety glass to show virtual information about real-time data from the machining process, that are augmented inside the workspace of an industrial CNC machine.

Another predominant field of application where AR is widely adopted is related to the inspection activities. In this context, various AR-based systems and tools have been developed in the last years for many applications regarding the inspection such as monitoring and control of industrial robots remotely [54], assistance for quality inspectors in the acceptance sampling process of products [55], for supporting assembly operations and, in turn, the inspection of assembled mechanical components [56], for assisting maintenance and inspection tasks for machines by displaying historical and current data of inspected machines [57] or workstations [58]. In addition, AR have been used as a supporting tool for spot-welding inspection activities for mechanical components by adopting a tablet mounted on the welding gun for visualizing useful AR guidelines to perform operations [59], and by using AR projectors to projects virtual information onto metal car parts by highlighting spot-weld locations [60,61]. Another application of the AR technologies for the inspection activities in the industrial construction field concerns the inspection of reinforcement structures [62], and segment displacement inspection of tunnelling construction [63]. Furthermore, inspection tasks also concern the detection of production and assembly errors and design discrepancies between the final physical products and those defined by the technical office. To this end, George et. al [64] have presented an AR-based system to assist an operator in the inspection of a product. In detail, some pictures of the real scene are firstly captured and then imported into the AR application. Afterward, CAD models are superimposed on the real images so that the inspection task can be manually performed by an operator. Nevertheless, a 3D discrepancy check is not possible since images only provide bi-dimensional data. Webel et. al [65] have proposed a solution for comparing CAD models with physical mock-ups, reporting differences between them, and transferring this information to CAD software. In particular, coordinates of 3D points are measured on the physical surface and then compared with those of the respective 3D model by means of a laser pointer combined with a stereo camera system. Moreover, detected differences can be indicated by adding annotations in the virtual environment. Unfortunately, the proposed solution is limited to single 3D points and is not thought for dense 3D difference detection. Better results have been obtained by using 3D information provided by depth cameras. Kahn et al. [66] have adopted a different solution based on an analysis-by-synthesis approach for 3D data acquisition. According to this approach, data provided by a depth camera are combined with data returned by a higher resolution 2D camera in order to detect variations amongst designed and built products. Although discrepancies are displayed in AR and overlapped onto the camera image in real-time, the low accuracy in the estimation of depth camera pose leads to bad results. Some improvements are described by the same authors in [67] to mitigate this problem, but the proposed solution is not applicable in the case of large products in an industrial scenario. In order to obtain better accuracy in capturing the geometry of a real object, Wasenmüller et al. [68] have developed an AR discrepancy check system using an RGB-D camera. It is able to reconstruct

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a 3D object in real-time and allows for an instant inspection. Unfortunately, the use of an optical tracking system to estimate the pose of the camera is unsuitable for an industrial application, as a calibration phase and specific working conditions are strongly required. In general, these systems are really accurate in the detection of discrepancies, but at the same time have several limitations: an effective AR visualization is not permitted; dedicated and expensive hardware components (depth cameras, optical tracking systems, etc.) are required; it is not possible to directly use these systems at the work station since no portable devices are adopted; skilled operators may be required for using these technologies. From this point of view, other systems have been proposed to overcome such limitations. It is really important to allow for the direct visualization of digital information on a device screen, as the user can pay more attention to both visual information and the inspection activity itself. This is possible when a mobile device (smartphone, tablet, etc.) is used. Additionally, the use of such devices could be very acceptable, as users are generally familiar with them. In this way a good usability may be reached and, at the same time, someone with no expert knowledge related to the AR technique may be able to use the inspection system. In this regard, an AR system to inspect pipes and improve safety in an offshore structure has been developed [69]. It provides design and current information to the workers on site. In particular, 3D models are displayed on the real prototypes also providing information about the status of a product, like temperature and pressure values. The testing phase carried out in a laboratory with experienced workers has confirmed the high potential of the system. In the same context, Olbrich et al. have designed an AR system to handle the planning and the installation of pipes in large ships [70]. Their solution allows for superimposing 3D models on partially manufactured pipes for a visual inspection. In this way, not only operators can identify potential differences, but also modify and adapt the virtual pipes locally. To this end, a dedicated tracking system based on the generation of a 3D reference map of the real environment was used. Although mobile AR systems able to visualize 3D models on the device screen have been developed in previous works, the authors don't provide any other information about the applicability of their systems on different components and there are no other validating results for the application of these solutions to the industrial field. A different solution was presented in [71] to provide helpful information to users during inspection activities. In fact, instructions and manuals are displayed on the device screen by guiding operators through a checklist of actions to be performed. Only information about components that are in the camera field of view is showed through the recognition of QR codes attached to physical items. Nevertheless, the inspection activity is performed by visualizing instructions, and not by visually comparing virtual models with the real products. In the same way, He et al. [72] have proposed an authoring user-friendly, AR-based system to support the inspection task. It makes it possible to augment 3D models on real objects. If models are not available on the database, the tool allows for scanning real objects from which, in turn, an approximate model is obtained. In any case, the operator, thanks to the superimposing of the virtual content on the real one, can add annotations about the detected errors. In addition, a marker-less approach is used to register virtual models in the real environment. This restricts the applicability of the solution to cases in which manufactured objects are very different from planned models. Therefore, the proposed system is not suitable for our goal. In addition, there

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are no user studies with end-users to evaluate its usability in an industrial scenario. So, its performances and limitations in such conditions are unknown. Although these AR-based systems can detect design discrepancies, they are not fit for an industrial scenario.

To this end, this paper proposes a novel AR tool specifically developed to assist operators during inspection activities. This tool simplifies the detection of discrepancies when an operator is working on-site by means of the superimposition of 3D models on the real prototypes and, when an error is visually detected, the user can add a virtual annotation by clicking on the virtual 3D models. The proposed tool runs on a consumer and cost-effective tablet, but it can also be applied easily to other mobile devices like smartphones. Additionally, this tool exploits a hybrid tracking technique based on the recognition of markers placed in the real environment. In this way, the estimation of device pose is well performed and, in turn, the integration of virtual models in the real scenario is accurate.

3. Material and methods

As mentioned in the introduction, this work aims to assist and support operators directly at the workplace during the inspection activities for the detection of production and assembly errors. The inspection activities, in fact, require time and high mental concentration especially when traditional paper-based methods are adopted. Furthermore, the probability that an operator can make mistakes increases as the geometric complexity of the product grows. For these reasons, in order to assess the proposed AR tool, a field experimentation has been carried out with end-users taking into account both objective and subjective standard metrics. In particular, the experimentation aims to evaluate its usability and perceived mental workload through the adoption of the SUS and NASA TLX standard questionnaires and the study of user performance while interacting and engaging with the AR tool.

3.1. AR tool

The AR tool has been developed according to a user-centred design approach [73, 74], which takes into account the user perspective since the early design stages in order to meet and satisfy users' needs and requirements, and ensure a high usability level to facilitate user acceptance of the tool. In particular, this tool has been developed on the basis of end-users' needs and opinions, acquired also in previous experimentations that were carried out both in the laboratory and on the field [12,13], and of the progress made in the field of augmented reality technologies. The proposed AR tool, in fact, is based on the ARCore™ framework [14], released by Google in 2018, which is an open-source framework adopted for building AR applications for Android™ devices, such as smartphones and tablets. Then, thanks to the widespread diffusion of these devices, there are advantages in terms of the user's acceptability of the proposed tool. Furthermore, Google has provided different ARCore™ SDKs for many of the most popular development environments, and in particular, for Unity®. The latter is a fully integrated cross-platform game engine, which offers a wide range of tools and features and allows creating interactive 2D and 3D applications by means of a visual editor and the use of

internal and external resources. Unity® can import and use the ARCore™ library to develop AR-based applications. Another advantage of such SDK is its hybrid tracking capability that combines visual information, acquired through marker-based and natural feature-based techniques, with inertial data provided by the inertial sensors (accelerometer, compass, gyroscope, etc.) mounted on the device itself to improve the accuracy of the device's pose estimation in 3D space. About the hardware, the AR tool runs on a Samsung Galaxy Tab S4 [75] mobile device, but it can be installed on both Android™ smartphones and tablets. This is, in fact, an Android™ tablet equipped with a Qualcomm Snapdragon 835 (Octa-core 4x2.35 GHz Kryo & 4x1.9 GHz Kryo) processor, a 13MP camera, and integrated motion tracking sensors (accelerometer, compass, gyro). Since all the computations are carried out on the device itself, there are no other external hardware components required for the data processing. The choice of the tablet is due to an explicit need expressed by the end-users who prefer displays larger than a smartphone screen. Additionally, the adoption of devices allows users to move in the real environment without any restrictions differently from other typical AR systems such as AR projectors and static screens. The following figure (Fig.1) depicts the software architecture of the proposed AR tool that consists of six main modules each one dedicated to one or more specific functions and capabilities.

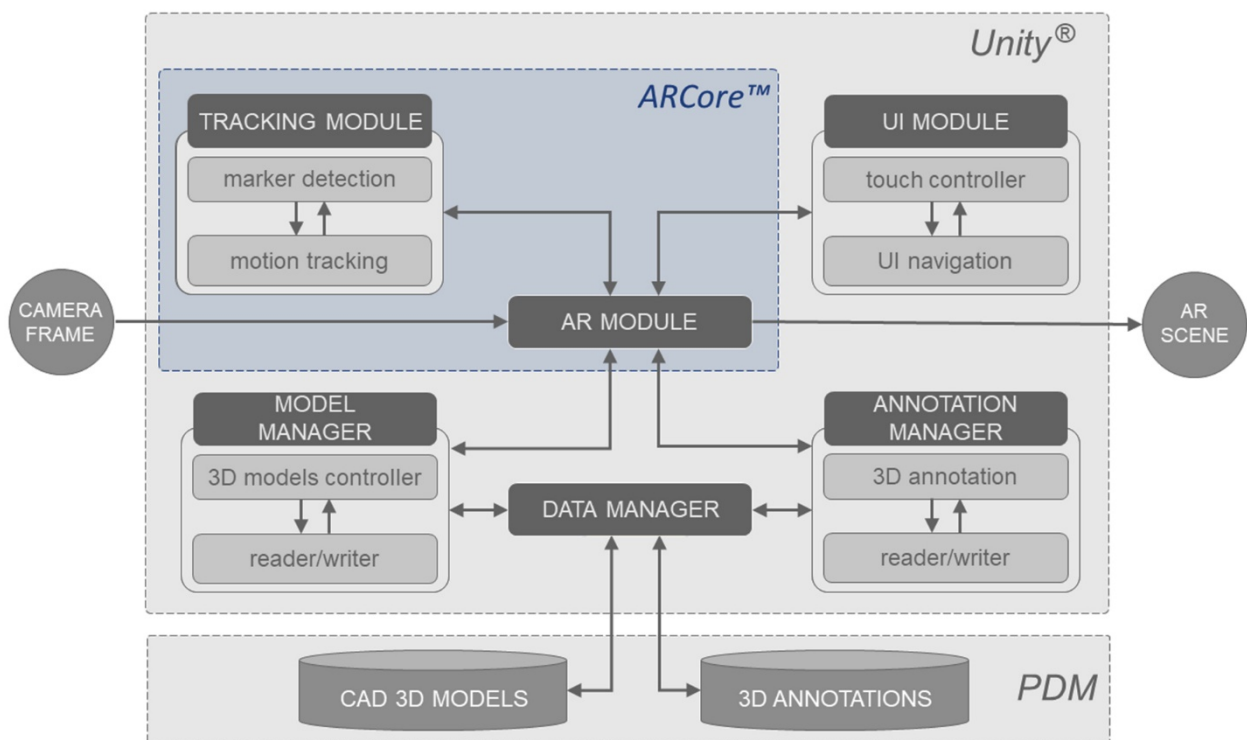


Fig.1. Software architecture

The AR module coordinates the different modules and is responsible for the AR visualization in which virtual 3D models are superimposed on the real physical scenario. Firstly, the AR module activates the camera of the mobile device from which a live video of the real-world scenario is obtained. This video stream is given as an input to the tracking module, which in turn adopts ARCore™ SDKs' routines, defined in the marker detection

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submodule, to automatically recognize up to 20 markers. When a marker is detected, the motion tracking submodule estimates the device pose, and then the integration of virtual objects in the real scenario is performed. The choice to implement a multiple marker detection approach is due to the fact that, especially in the case of large products, a single marker is not sufficient to ensure a precise registration of virtual models on the real ones. This happens because the tracking module adopts a hybrid tracking process, called simultaneous and localization mapping (SLAM) provided by ARCore™ SDK, that blends inertial measurements (inertial tracking) with data provided by processing images and detecting natural features (visual tracking) to estimate the device pose. Unfortunately, the tracking performed with the inertial sensors accumulates drift error over time and this negatively affects the overall device pose estimation. Thanks to the adoption of different fiducial markers, positioned within the real scenario prior to start the AR application, the drift error is reset each time a marker is detected. The 3D models, designed by the technical office, are imported from the PDM (Product Data Management) through the data manager module. These files are then sent to the model manager module that reads and converts the 3D models for the AR visualization by means of the reader/writer component. The 3D models controller manages all proprieties of 3D models in terms of positioning, parent/child relations, and graphics appearances. In this latter case, it allows the user to customize colors and transparency level by acting on the alpha channel of the color assigned to the virtual model. To this end, this module operates on the mesh renderer components that are associated with each 3D model displayed on the screen. All these proprieties are therefore stored within the CAD 3D models database for further uses. Before the running of the AR tool, it is necessary to perform a preliminary operation to prepare the virtual scene by adding to the 3D models the geometry of the QRcode markers with the same position in which they are fixed in the real scenario. This operation can be performed by the technical office through a CAD system and then make this data available for the AR tool by means of a PDM system. About the data manager module, it relies on the SQLite API (Application Programming Interface), embedded in the SQL (Structured Query Language) database engine, to administer data exchange between the model manager and annotation manager modules and their related databases. The annotation manager module deals with the managing of 3D annotations by allowing the user to add, update, or delete them. In particular, it consists of two submodules: the 3D annotation and the reader/writer module. The first one implements Raycast functions, provided by the MonoBehaviour class of the Unity® engine, to recognize user selection of the 3D virtual models. In particular, the user's touch generates an invisible ray that hits the virtual component on which a 3D virtual annotation can be placed. Furthermore, each annotation presents predefined set of properties that can be customized by the users and are automatically stored in the dedicated database through the reader/writer component. In this manner it is possible to share this information with the technical office and to reload a working session to continue the inspection activity. The UI (user interface) module consists of two submodules: the touch controller and UI navigation. The first one is dedicated to the recognition of user's touch on the device screen. The second one deals with the managing of panels and command buttons that appear on the screen during the use of the tool. As depicted in the figure 2, most of the screen is dedicated to the live video stream for the AR visualization, while a few command

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buttons have been placed at both sides of the screen. On the right side of the screen, two indicators provide information about the battery level and the ID of the latest detected marker and a command button to capture a snapshot of the screen. Whereas the menu button placed on the left side of the screen allows the user to open a drop-down list to: visualize a list of the 3D models loaded in the current session; customize the visualization of the 3D annotations; upload 3D annotations on the dedicated database; quit the application.

The figure 2a depicts a typical situation in which an operator is using the AR tool to inspect a flanged pipe system. A purple colored 3D model, superimposed on the real physical environment, represents the position and the dimensions of the component as it has been designed by the technical office. The user can then move around the inspected object and look at this from different perspectives to verify the position of the components and possibly detect design discrepancies between the physical components and the augmented 3D models. In order to simplify the inspection activity, the AR tool allows the operator to improve the visibility and the ability to discern objects by customizing color and transparency level of the augmented 3D models. Figure 2b depicts the operator while inspecting a valve assembly. Thanks to the superimposition of the green colored 3D models on the physical components, the operator can readily detect the assembly error due to a 180° rotation of the physical valve with respect to its position as defined by the technical office. When a design discrepancy is identified, the operator can add a 3D annotation, in the form of a 3D virtual thumbtack placed directly on the virtual model, that records and shares this information with the technical office.

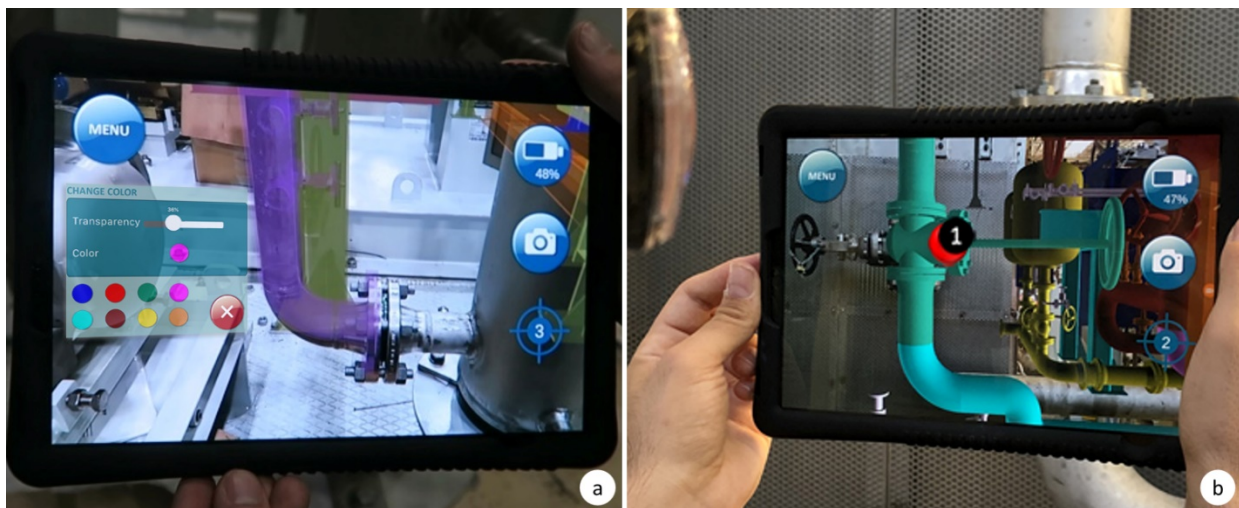


Fig.2. The operator while adopting the proposed AR tool to inspect a flange system (a) and the assembly of a valve (b)

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3.2. Case study

The experimentation has been conducted with end-users on an industrial case study at the Baker Hughes plant located in Vibo Valentia (Italy). In particular, the assembly inspection of an auxiliary baseplate system has been selected as a case study. This system, 14 meters long and 6 meters wide, works as a starting system for a gas turbine by providing oil lubrication of turbine bearings and managing its oil pressure and temperature.

Because of the large dimensions of the baseplate system, only two sides of the system (their 3D model is depicted in figure 3) has been taken into account to carry out the user study by analysing human performance in target acquisition tasks while interacting with the proposed AR tool. Five markers have been placed 1.5 meters apart in order to be easily detected by the AR tool, whereas the operator moves freely and naturally following the perimeter of the system. In particular, rigid plastic QRcode markers, of size 150mm x 150mm x 1 mm, have been placed on the physical components in a simple and fast way by using an adhesive strip to ensure durability without damaging the surface.

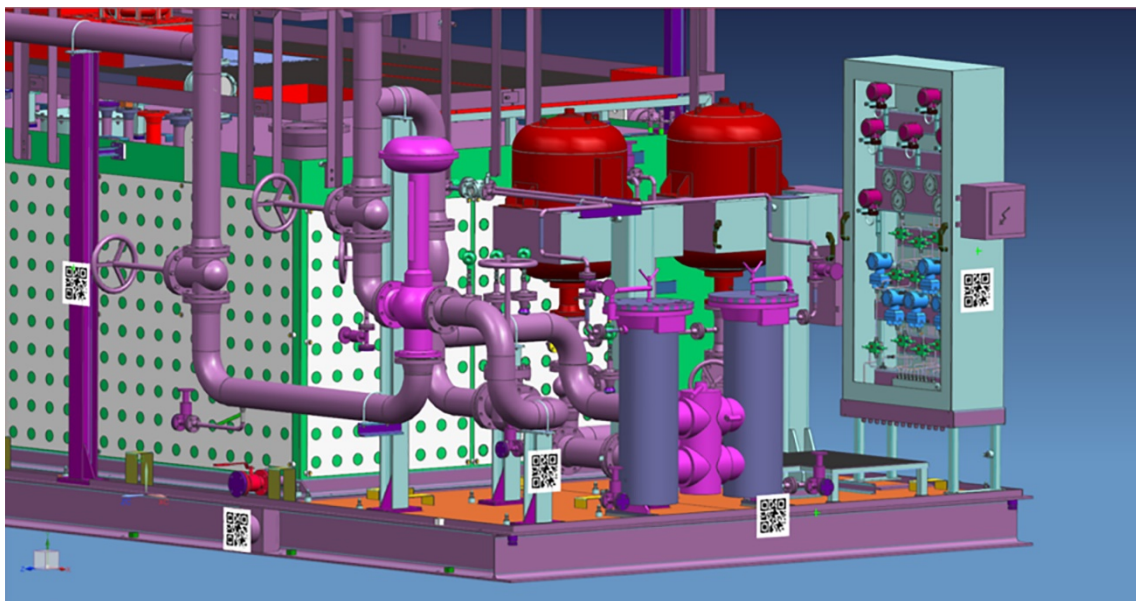


Fig. 3. 3D model of the auxiliary baseplate system adopted for the user assessment of the AR tool. © 2021 Baker Hughes, LLC - All rights reserved

3.3 Participants

A total of sixteen voluntary participants were recruited among engineers and factory workers of the Baker Hughes plant of Vibo Valentia. The number of participants has been defined on the basis of the most influential articles on the topic of sample size in user studies [76-79] and its minimum value has been chosen according to a technique for accurate adjustment for small-sample size [80]. Based on these recommendations, the test sample size has been calculated on a problem discovery rate of 95% and it has turned out to be of eight participants. Two representative user groups have been involved in the user study:

G1: 8 engineers (4 males and 4 females) with average age 30.5 (min 23, max 46, SD=6.61);

G2: 8 factory workers (all males) with average age 40.9 (min 23, max 53, SD = 10.51).

All the participants were skilled in the use of smartphone and tablet devices. All of them, however, were novices to AR technology.

3.4 Procedure

The user study is composed of three main steps: demo, training, and test.

Demo – in the first step, a tutor provided each participant with a brief demonstration (Fig.4a), usually about 2-3 minutes long, about the main functionalities of the AR tool.

Training – in the second step, each participant was free to familiarise with the tool without any limitation in time. A training at the beginning served as a buffer for acquiring skills with the proposed AR tool and for getting accustomed with its user interfaces.

Test – in the third step, each participant performed an indicated set of six tasks (Fig.4b):

- 1) framing a marker and visualizing the AR scene;
- 2) detecting a design discrepancy and adding the relative 3D annotation;
- 3) taking a picture of the design discrepancies detected during task 2;
- 4) changing the size of the 3D annotations added during task 2;
- 5) framing *marker 4* and hide the 3D model of the *Filter* component;
- 6) sending picture and 3D annotations to the technical office.

A human assistant supervised the test and took notes about the time and the number of errors made by users during the performance of each task. When the tasks were completed, each participant was invited to complete a questionnaire and to perform a one-on-one personal interview aimed at obtaining their personal opinions about the proposed AR tool.



Fig.4. Our tutor while providing a demo of the AR tool (a); and a participant while performing the tasks (b) © 2021

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3.5 Measures

The usability of the proposed AR tool has been evaluated on the basis of the international usability standard ISO 9241-11 [81] that takes into account both objective and subjective metrics. According to this standard, the usability's efficiency and effectiveness have been evaluated through the measure of the completion time, i.e., the time in seconds to complete a task, and the number of errors made by each participant while performing the tasks, respectively. In addition to these objective measures, a questionnaire to assess the subjective usability has been developed using as foundation standard questionnaires which definition is based on psychometric methods [82]. To this end, the standard SUS questionnaire [83] has been adopted. It contains 10 mixed tone items, where odd numbers have a positive tone while the even numbers have a negative tone, with a 5-point Likert scales anchored at the end points with the terms "Strongly disagree" for 1, "Strongly agree" for 5 [84]. These values are summed and converted, by means of multiplication factors, to obtain an overall score ranging between 0 and 100 [85]. This range is then broken down in different grades [86] of usability indicated with an uppercase letter from F (absolutely unsatisfactory) to A+ (absolutely satisfactory).

In addition to the usability assessment, the user study aimed to evaluate the subjective mental workload through the adoption of the NASA TLX standard questionnaire [87]. It allows for deriving the overall workload score based on a weighted average of ratings on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. To reduce the time required to complete this questionnaire and prevent this phase from becoming frustrating for the participants, a modified version of TLX, namely RTLX (Raw Task Load Index) questionnaire [87-90] has been adopted. See Table 5 in the appendix for the detailed NASA questionnaire administered to operators during the experimentation.

4. Results and evaluation

Descriptive statistics, t-test, and analysis of variance tests have been used to analyse the effects of the AR tool on time and error rate. All analyses have been conducted using the statistical packages Microsoft Excel and IBM® SPSS. The statistical significance level was set at $p < 0.05$. The results of t-tests have been reported in tables where Sig. is the probability value (p-value) computed using the t distribution.

4.1 Usability results

The following figure (Fig.5) shows the results of the average completion time required by G1 and G2 groups to perform each task.

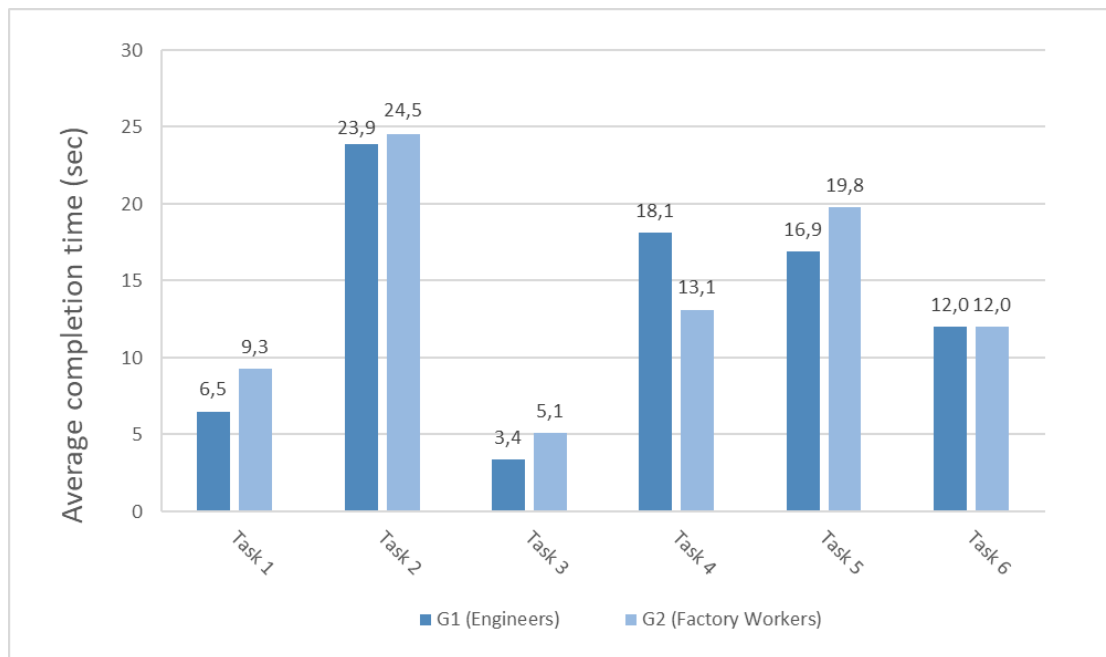


Fig.5. Average completion time to perform each task by G1 and G2 groups.

The results show that, in almost all tasks, it takes a longer time for workers to complete operations required to perform the experiment. For task 4 only, engineers require more time than workers. While in the case of the last task (6), both groups required the same amount of time. Although the graph (Fig.5) shows such differences, these are not confirmed by an independent *t*-test analysis which results, depicted in Table 1, indicate that there is no statistically significant difference in the completion time between the two groups. **Table 1** Independent samples *t*-test analysis of average completion time between G1 and G2 groups

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
Sig.	0.199	0.928	0.424	0.471	0.455	1.000
<i>t</i> value	-1.347	-0.092	-0.824	0.741	-0.769	0.000

In particular, as shown in the previous figure, the execution of task 2 has required on average the highest completion time with a mean time of $M = 23.9$ ($SD = 17.4$) and $M = 24.5$ ($SD = 8.3$) for the G1 and G2 groups respectively, which does not present a statistically significant difference ($t(14) = -0.092$, $p = 0.928$). This task consists of the identification by the user of at least one design discrepancy and the addition of the relative 3D annotation. The reason why the users need more time for this task is the fact that the completion of this activity requires the accomplishment of various operations in sequence: firstly, the search for the discrepancy between the virtual models and the physical product; secondly, the selection of the 3D model to which an annotation needs to be added; and finally, completing the predefined text fields necessary to validate the addition of the note. The second highest value for completion time is relative to task 5 in which the user is invited to frame a specific marker and customize the physical appearance of a 3D model. Also in this case there is no statistically

significant difference between the two groups ($t(14) = -0.769$, $p = 0.455$), and the required amount of time can be justified by the very nature of the task that consists in searching for a specific physical marker to be framed with the AR tool, and a specific virtual component to look for in the assembly by moving within the real scenario. Completing tasks 1, 3, 4, and 6 require less time than others by both groups since these are one-button-click operations that call for the selection of a specific functionality to search for among those present in the AR tool's UI. In short, it can be said that the completion times scored by end-users of both groups are similar, there is no statistically significant difference, and they are consistent with the complexity of the tasks.

The following figure (Fig. 6) depicts the results of the average number of errors made by end-users while performing the predefined tasks. The selection of a command button different from the correct one in order to complete the task has been considered an error. The request for a suggestion by a user has been considered an error, too.

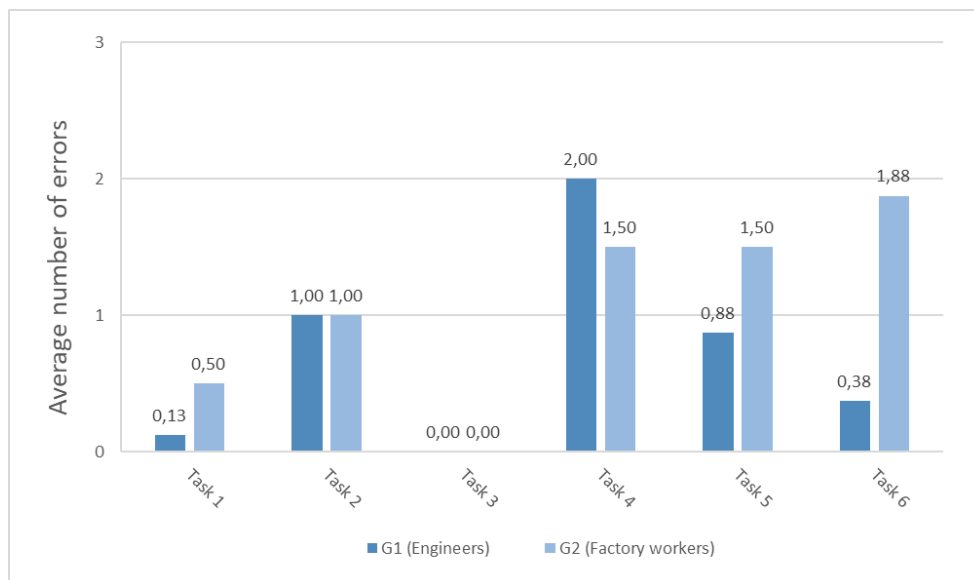


Fig.6. Average number of error for each task

As depicted in figure 6, the highest number of errors occurred during the execution of task 4 in which users were asked to customize the visual properties of a 3D annotation added on the virtual 3D models. In particular, the workers and engineers have concluded this specific task with an average error of $M = 2.00$ ($SD = 2.39$) and $M = 1.50$ ($SD = 2.07$), respectively. As emerged by users' comments gathered during personal interviews, the large number of errors occurred in task 4 were due to the fact that users instinctively clicked on 3D models instead of operating on the dedicated menu. Such error is common in both groups; in fact, an independent sample t-test (Table 2) shows that there is no significant difference in the number of errors occurred performing task 4 between the two groups ($t(14) = 0.447$, $p = 0.662$). The second largest number of errors was committed by workers during the execution of task 6 in which the users were invited to send the collected data to the technical office by selecting a dedicated functionality. It emerged from the users' interviews that they had problems with attaching data, especially photos. Also in this group, even if the number of errors made by the

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G2 group is higher than the one of the G1 group, there is no statistically significant increase from G1 ($M = 0.38$, $SD = 1.06$) to G1 ($M = 1.88$, $SD = 2.47$) ($t(14) = -1.576$, $p = 0.137$). It should also be noted that both groups made no errors while performing task 3. This was probably due to the fact that the command button implemented in the AR tool to take pictures is very similar to the native functionalities made available by common smartphones and tablets, therefore participants were already used to it.

Table 2 Independent samples t-test analysis of error rates between G1 and G2 groups

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
Sig.	0.362	1.000	-	0.662	0.382	0.137
t value	-0.942	0.000	-	0.447	-0.902	-1.576

The following table (Tab.3) shows the results of the SUS questionnaire completed by participants after performing all tasks. In particular, as described in Section 4.3, each participant was asked to answer ten standard questions by indicating a value ranged between 1 and 5. Then, the values provided by each participant have been converted in order to get the SUS score ranged between 0 and 100. In particular, as showed in table 3, the SUS mean values of the G1 and G2 groups are respectively 86.56 and 85.94.

Table 3 SUS questionnaire results

Group	SUS score average	Standard deviation
G1	86.56	14.94
G2	85.94	18.47

4.2. TLX results

The following figure (Fig.7) shows the results of the NASA TLX questionnaires for the estimation of the cognitive workload perceived by the participants during the experimentation. In particular, as mentioned in Section 4.3, this standard questionnaire allow for evaluating three dimensions related to the demands imposed on the subject (Mental, Physical, and Temporal Demands) and three to the interaction of a subject with the task (Performance, Effort, and Frustration) using a 100-point scale. The following figure (Fig.7) depicts the results of the NASA TLX questionnaire. However, it can be observed that all dimensions are under 15 points.

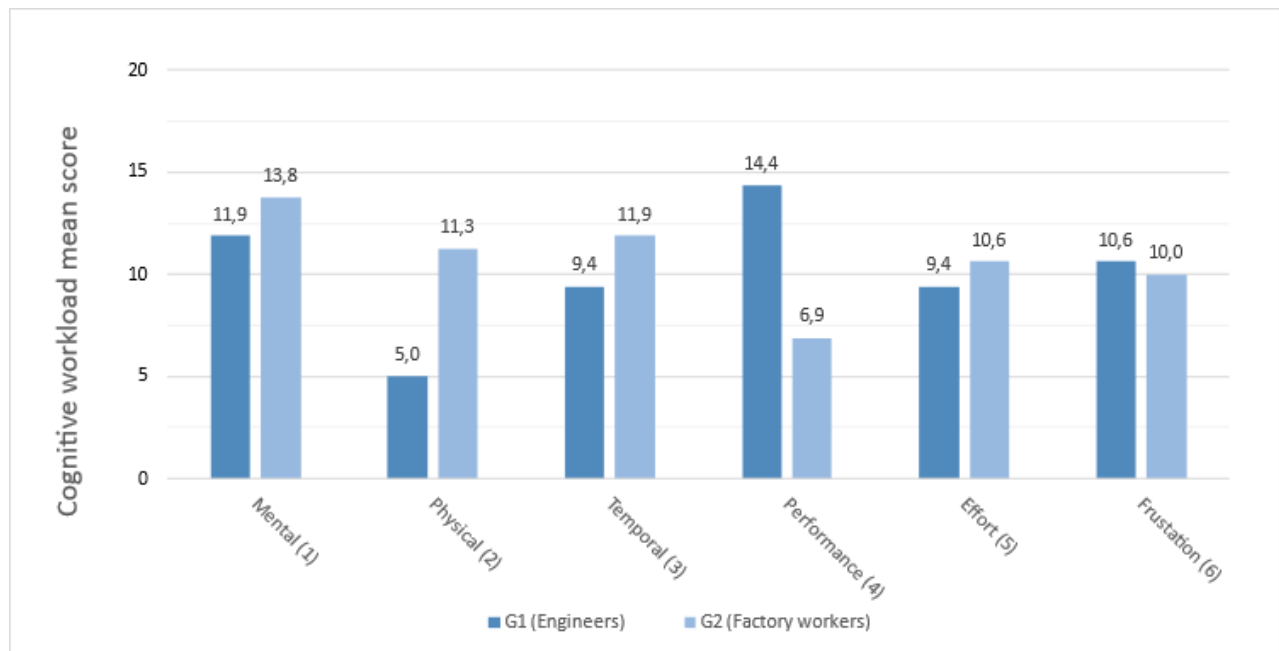


Fig.7. Cognitive workload of the participants while performing the test

As depicted in the figure (Fig.7), the highest value is reached by the G1 group for the performance factor which presents an average score of $M=14.4$ ($SD = 17.8$), while the overall mean score of the cognitive load, taking into account all the six factors, is 10.1. About the G2 group, the highest value is related to the mental factor with a mean score equal to $M=13.8$ ($SD=17.3$), while the overall mean score of the cognitive load is equal to 10.7. Then, the G2 group scored an overall cognitive workload slightly greater than G1 one. In particular, G2 group perceived a greater mental, physical, temporal, and effort workload than the G1 group. On the contrary, G1 group presents higher levels of cognitive workload specifically for the factors related to performance and frustration.

Table 4 Independent samples t-test analysis of the cognitive workload between G1 and G2 groups

	<i>Mental</i>	<i>Physical</i>	<i>Temporal</i>	<i>Performance</i>	<i>Effort</i>	<i>Frustration</i>
Sig.	0.807	0.334	0.712	0.282	0.765	0.903
t value	-0.249	-1	-0.377	1.163	-0.304	0.124

The results shown in figure 7 have been submitted to an independent t-test analysis which results are grouped in the following table (Tab.4). What emerges is that although some differences are depicted in figure 7, the results of a t-test analysis show that there is no statistically significant difference in the cognitive workload between the two groups. Furthermore, an analysis of variance was conducted to compare the six factors scored by each group to identify possible differences among them. A one-way ANOVA showed that there is no

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statistically significant difference among the factors that contribute to quantifying the overall cognitive workload perceived by participants: $F(5) = 0.739$ and $p=0.599$ and $F(5)=0.217$ and $p=0.953$ for G1 and G2 groups, respectively. In conclusion, it is possible to confirm that both groups perceived very low levels of cognitive workload. This result has been achieved thanks to an intense design work and testing carried out by involving the end-users in all the different design stages. Furthermore, this outcome is consistent with the results of the usability study, hence demonstrating that this tool is intuitive and easy to use.

5. Discussion and limitations

In this section, the results of the field experimentation are discussed, benefits for industry are outlined as well as limitations of the proposed AR tool, and possibilities for further works. As abovementioned, the proposed AR tool has been assessed by means of quantitative and qualitative standard metrics with the involvement of end-users that have performed the experimentations in their working environment on a real case study. In particular, the quantitative metrics and the SUS questionnaire have been adopted to assess its usability while the NASA-TLX standard questionnaire to quantify the perceived mental workload required by the user while interacting with the AR tool.

About the quantitative metrics, the results show a low number of errors occurred during the interaction of the user with the proposed tool. This positive result proves that the tool is easy and intuitive to use, also in the case of novices to AR technologies. This achievement has been reached thanks to two main factors: the tool has been developed taking into account needs and suggestions of the end-users that have been involved in all the various stage of the design development process and it represents the evolution of a number of prototypes previously tested to better comprehend users' needs and conditions of use; the AR application has been intentionally developed to run on tablet devices in order to take advantage of the confidence that users have with these devices, in fact, all the participants, regardless of their age, were skilled in the use of smartphone and tablet devices. About the average completion time required to perform the predefined set of tasks, both groups scored similar results that are consistent with the complexity of the operations. In particular, the second task, aimed at the detection of a design discrepancy intentionally introduced on the virtual models, showed a very low time considering the size of the case study and the inspection area. These positive results have been clearly expressed also by the participants who have expressed a positive opinion regarding the immediacy with which it is possible to visually identify design discrepancies and a wider acceptance regarding the introduction of this tool as a support to the inspection activities. These results are consistent too with a previous study aimed to evaluate the efficiency of the AR technology, in terms of task completion time, when compared with traditional tools adopted for inspection activities in the Oil&Gas sector [13]. The high level of usability of the proposed AR tool has been confirmed also by the results of the SUS questionnaires. In fact, both groups reached very similar values just over 85 in the range from 1 to 100. For the interpretation of these results, validation studies demonstrate that an acceptable SUS score is about 70 [91,92]. Nevertheless, a more stringent criterion has been used to this end. In particular, it has been adopted a curved grading scale [85] that correlates

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the SUS score to the usability perceived by users. On the basis of this criterion, the SUS mean values of both groups have overcome the threshold of 84.1 which identifies the lower limit of the range identified by the letter A+. This means that the participants are very satisfied with the usability of the AR tool. This positive result was further confirmed by the personal interviews carried out at the end of the experiment during which all participant explicitly expressed their positive opinions regarding the use of the tool, and in particular its usability and implemented functionalities as they provide a practical and effective support for the inspection activities. In conclusion, on the basis of these considerations, it is possible to validate the assumption that the proposed AR tool could be efficiently adopted to supports workers during the inspection activities for detecting design discrepancies and assembly errors.

About the NASA TLX questionnaire, this study is the first to explore the adoption of an AR-based tool technology to support inspection activities from the perspective of perceived cognitive workload. In fact, the purpose of the user studies is not only to demonstrate the AR tool is easy to use and satisfies end-users' needs but also to investigate its impact in terms of user's mental workload. In particular, as detailed in Section 4.2, the participants to the experimentations perceived very low levels of cognitive workload. This positive result confirms that the use of AR minimizes the cognitive load of divided attention induced in attending to both the physical prototype and the related design data. This is due to the fact that divided attention tasks, as in the case of traditional inspection paper-based instruments, demand a high mental workload [10] and increase the difficulty rather than simplify the operations [11]. As a consequence, this leads to a reduction in the efficiency of the user's processing capacity. Furthermore, for users with poor divided attention, any interference may alter the task that they are doing simultaneously. In this case, the choice of the tablet, and therefore a limited viewing area, does not represent a limitation of the proposed tool but it favors the user's concentration because of the selective mechanism of the human brain that can elaborate only a limited amount of visual information of the retinal image, by paying attention to some stimuli while ignoring others [93, 94]. At the same time, as detailed in Section 2, different AR technologies developed for the monitoring and inspection activities have the capability to superimpose virtual data directly on the real environment. Nevertheless, digital projectors and displays require to be placed in fixed positions and are characterized by limited areas of usage [51,60,95]. On the contrary, wearable devices provide more freedom of movement, and the user can use both hands while watching the superimposed images but they suffer from bad ergonomics and excess weight that can cause visual fatigue and impact concentration performance [96,97] and can lead to distraction or disorientation [98,99]. These outcomes for the workers are then not only essential for decreasing cognitive load and increasing focus, but it is also essential for ensuring safety in the manufacturing environment. In fact, the proposed AR tool has been conceived to provide greater freedom of movement to the workers, who can use it also for the assessment of large-size products going inside and around them, with a high level of usability satisfaction in order to foster user acceptance.

While having significant implications for the industrial sector, this solution has also limitations that indicate directions for future research. A first limitation, emerged during the experimentation activities, is due to the

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influence of the environmental light that worsens the performance of the AR tool. In fact, very high lighting conditions cause surface reflections which could result in the failure recognition of markers and can negatively impact the quality of the visual tracking by causing misalignments among virtual and real objects. Misalignments have been reported by end-users while performing experimentations also in the case of small components, with a size smaller than 3 centimeters. Another limitation is related to the presence of poor natural features that are used by ARCore™ to track the device pose when the visual markers are not in the camera field of view. In fact, large feature-free and homogeneous surfaces usually don't allow an accurate pose estimation and result in a low-quality AR visualization. Nevertheless, this issue can be effectively solved by adding more artificial features to the real environment. Another limitation is related to the visual perception of the augmented 3D models. In this regard, it has been noted that the adoption of dark colors, assigned to virtual objects, may result in an insufficient text color contrast for the detection of design discrepancies. On the basis of these limitations, future works are focused on the improvement of the tracking accuracy by investigating the adoption of object recognition techniques. Furthermore, it will be very meaningful to compare and test, with the involvement of end-users, different approaches to augment 3D models on the virtual scene and to optimize their colors and lighting parameters.

6. Conclusions

In this paper, an innovative AR tool has been proposed to assist workers at the workplace during inspection activities of industrial products. In particular, by superimposing virtual 3D models on the correspondent physical prototypes, workers can easily detect production and assembly errors, and then add 3D annotations directly on the virtual models to report and share this information with the technical office.

This AR tool has been developed by using the Google ARCore™ SDK in order to ensure, in the first place, its compatibility with commonly used devices, e.g., smartphones and tablets, for which workers are already trained and, secondly, to take advantage of the hybrid-tracking techniques that combine vision- and sensor-based methods to improve the reliability of the AR visualization. Furthermore, the proposed AR tool adopts multiple markers to minimize tracking errors and therefore to provide greater freedom of movement to the user that, as confirmed by the case study adopted for the experimentation carried out under real operating conditions, can adopt this solution also in case of large-size products.

The proposed AR tool has been assessed on a real case study, representative in terms of complexity of the inspection activity usually carried out in the real condition of use in the Oil&Gas sector, with the involvement of end-users. In particular, the tool's capability to support workers has been evaluated through a usability study based on objective and subjective metrics, and a measure of the cognitive workload quantified subjectively using the NASA questionnaire. The user study has demonstrated that both groups have perceived similarly high levels of usability and low cognitive demand. These positive results have been confirmed also by the personal interviews during which all participants explicitly expressed their positive opinions regarding the use of the proposed AR tool, and in particular its usability and implemented functionalities as they provide a

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practical and effective support for the inspection activities. In short, these results are encouraging toward future integration of the proposed AR tool in the industrial scenario to enhance and stimulate the efficiency of the workers' skills during inspection activities.

Appendix A.

Table 5 – NASA TLX questionnaire

#	Dimension	Question
1	Mental Demand	How mentally demanding was the task?
2	Physical Demand	How physically demanding was the task?
3	Temporal Demand	How hurried or rushed was the pace of the task?
4	Performance	How successful were you in accomplishing what you were asked to do?
5	Effort	How hard did you have to work to accomplish your level of performance?
6	Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?

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