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Evaluating the effectiveness of Spatial Augmented Reality in Smart Manufacturing: a solution for Manual Working Stations

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Abstract Augmented Reality (AR) is a key technology for the development of Smart Manufacturing. One of the main advantages of AR is that it can help workers to accomplish several tasks, making it possible the shift from mass production to mass customization. However, it is still not clear how these promises can be fulfilled in an industrial scenario. In particular, the question about which display solutions fit better the industrial constraints remains open. Based on literature overview, laboratory experiments and feedbacks from industrial companies, we supported the use of Spatial Augmented Reality (SAR), designing a prototype intended to be used for Manual Working Stations of the future Smart Factories. This work presents the evaluation of the effectiveness of conveying technical instructions with this SAR prototype as compared to paper manual. We run a within-subjects experiment with 16 participants to measure user task performance (completion times and error rates) and to collect subjective evaluation. We projected technical information on a motorbike engine during a 7-tasks maintenance procedure. Our results proved that SAR technology improves operators' performance respect to a paper manual and that users well accept it. We found that SAR is more effective for difficult tasks than for simple ones and that the main advantage of SAR is related more to the reduction of error rates than to completion times. These results confirm the goodness of our design choices; then our prototype can be a valid candidate solution for a Smart Manufacturing application.

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1 Introduction

Augmented Reality is one of the nine enabling technologies that will power the transformation supported by Industry 4.0 initiative [1]. In this transformation, sensors, machines, workpieces, operators, and IT systems will be connected to the value chain beyond a single enterprise. In particular, there are specific industrial areas where the visualization of information through AR is very effectiveness respect to other technologies: examples are remote assistance [2], [3] and localization of points for inspections [4]. These AR-supported systems are currently in their early stages, but we strongly believe that, in a next future, companies will make much broader use of AR to provide workers with real-time information to improve decision making and work procedures. In fact, the use of AR minimizes cognitive load and issues of divided attention induced in attending to both the real working space and the information space on the manual. Divided attention is the ability to respond simultaneously to multiple tasks or multiple task demands and is regarded as the highest level of attention [5].

In the literature, we found several successful demonstrations of the use of AR in the medical domain, military training, telerobotics, entertainment, maintenance, and manufacturing [6]. However, Augmented Reality solutions are still struggling to reach the factories. This issue is mainly due to display solutions that still do not fit with strict industrial constraints about ergonomics, color coding, training of operators, the reliability of proposed solutions.

Common AR applications use Head-Worn Displays (HWDs), which suffer from bad ergonomics, low resolution, an excess of weight, limited/fixed focal depth

[7]. Industrial operators have to wear the HWD for long sessions and, for this main reason, industries do not well accept AR with these displays.

An alternative approach to HWD is to use handheld devices like smartphones and tablets. Although this kind of AR is very easy to implement due to the availability of low cost and powerful devices, in practice it has various limitations. One of the most important is that operators should employ one or even two hands for the visualization, thus limiting their ability to operate.

In a previous work [8], we experimented a setup with a large screen to avoid the use of HWDs and handheld devices. We found that the use of an AR approach compared with a traditional approach based on paper manuals produces a significant improvement in operators' performance for maintenance tasks.

However, the use of a large screen is not an easily scalable solution in various industrial scenarios: not everywhere there is enough space for a large screen. Furthermore, it suffers from a high angular offset, i.e. the offset between the real world being observed and the display through which the user sees it. A high angular offset may lead to alignment problems: users may not readily understand the relationship between what is seen directly in the real world and what is shown on the screen when comparing both, which may require difficult mental rotation and scaling [9].

A display solution that does not suffer from the problems above (ergonomics, not free hands, angular offset) is represented by Spatial Augmented Reality (SAR) using digital projectors. Thus, it could be an optimal solution for the visualization of both instructions and technical information directly on the industrial workbench. In a real working environment, operators stand in front of the workbench, and currently, instructions on monitors assist them. Monitors are usually placed on their workbenches or tool carts. SAR makes use of digital projectors to superimpose virtual data (such as text, symbols, indicators) directly on the real environment, as early found by Bimber and Raskar [10].

The main disadvantages of SAR, as pointed out by Kruijff et al., are: i) surface-based distortions; ii) brightness, contrast, and visibility of projection; iii) lower color fidelity; iv) higher latency; v) limited FOV of the projector; vi) registration [9].

Surface-based distortions may cause problems with legibility of projected text. Thus we already made a study to evaluate if it was possible to read in an effective way instructions directly projected on the workbench. It revealed that projecting text directly on workbench surfaces guarantees the same legibility performance of a traditional LCD monitor [11].

We then designed an SAR workbench [12], trying to solve all the other potential issues. It consists of an aluminum structure that holds a projector and a camera that is intended to be mounted on Manual Working Stations (MWS). Common operations that are accomplished into an MWS are assembly, welding (especially spot welding), packing, testing, repairing, inspecting. The camera, using a tracking algorithm, computes in real time the position and orientation of the object while the projector displays the information always in the desired position.

The main contribution of this work is the evaluation of the designed SAR workbench, to verify if the proposed solutions were effective to aid users in the visualization of technical instructions. In fact, it is known for a long time that AR can help for the support of technical operators. However, this was plenty demonstrated for traditional AR, but scarcely for SAR. The distinction is not negligible because the visualization capabilities of SAR are poorer than those of traditional AR. For example, it is not possible to display mid-air virtual objects, but only 2D objects on a physical surface. Furthermore, surface-based distortions remain an issue, and the user could misunderstand the projected instructions.

Therefore, we designed an experiment to evaluate user performance, regarding task time and error rate, and user acceptance obtainable with the SAR interface, comparing them with those obtained with a traditional paper manual.

We organized the paper as follows. In Section 2, we present related works on user evaluations of AR and applications of SAR in the industry. Then, in Section 3, we describe the design of the experiment. In Section 4, we illustrate the results achieved in the experiment. Finally, in Section 5, we provide a detailed discussion and our conclusions.

2 Related Works

In this paper, we organized the related works into two sections: in the first section, we present the related works regarding user evaluations of AR systems in industrial applications; in the second section, we present the related works about the use of SAR in the industrial domain.

2.1 User evaluation of AR in the industry

The integration of Augmented Reality with assembly and maintenance operations is a topic that has been widely addressed in the last years. Wang et al. [13] presented an extensive review of researches on AR in assembly tasks reported between 1990 and 2015. They divided the literature related to AR assembly research into three categories: AR assembly guidance, AR assembly training, and AR assembly simulation, design, and planning. At the end of this review, they remarked the importance of the familiarization for both users and developers with the new proposed AR assembly solution.

Fiorentino et al. [8] performed a user evaluation test using video-based AR with a large screen display near the operator workbench, and a combination of multiple fixed and mobile cameras. Participants performed similar operations in two modalities: paper manuals and AR instructions. In the AR mode, visual labels, 3D virtual models, and 3D animations supported tool selection, bolts removal, part (dis)assembly. Statistical analyses showed that AR instructions displayed on the large screen significantly reduced participants' overall performance time and error rate. Furthermore, user acceptance of the AR system was higher than the paper manual.

Tang et al. [14] compared assembling operations of toy blocks with four different instructional modes: 1) printed manual, 2) 2D static images on a laptop with 15'' display, 3) static images on a see-through HMD and 4) a spatially aligned 3D models on the see-through stereo HMD using magnetic tracker (full AR). They measured: time of completion, the number of errors and mental workload. As far as regards the time of completion, their test verified a relevant improvement passing from the paper manuals to the computer supported ones. However, only with full AR, there was a significant reduction even of error rates and mental workload respect to printed manual. On the contrary, there was not a significant time advantage of full AR comparing with other computer-assisted approaches.

Tegeltija et al. [15] implemented AR in the disassembly of a heating circulation pump. The experiment was carried out on three different types of the pump, and with the disassembly procedures done in four variant modes. These modes were the combination of using AR and hard copy documentation and performing the disassembly sequence with the worker who has and has not previously performed pump disassembly. Observing the results of the experiment, the authors concluded that the implementation of AR in the area of disassembly systems could lead to a series of time reductions in the disassembly process. They did not make analyses about the accuracy of the procedures.

Elia et al. [16] proposed a multi-criteria model to support quantitatively production managers and researchers in evaluating the performance of different AR devices based on both technological and organizational performance required by the specific manufacturing process. They developed an expert based tool to support, in a more efficient way, the design of AR applications in specific manufacturing issues. They validated the model with a test case of a complex maintenance task carried out in a harsh workplace. Even if their test case aimed only to demonstrate the actual applicability of the proposed multi-criteria model, their results are interesting for our work. In fact, they found that projectors are the best AR alternative in a set also containing HWDs, haptic and handheld devices. Projectors were also the most 'agile' devices, whereas their reliability was lower respect to handheld and haptic devices.

2.2 Applications of SAR in the industry

In the recent years, we are assisting to an increase in the number of works where SAR is used to perform assembly and maintenance tasks.

The traditional use of SAR in the industry is for the spot localization in spot-welding operations. Doshi et al. [17] improved the precision and accuracy of manual spot-weld placements with the aid of projected visual cues. The prototype system was deployed at a General Motors (GM) plant. They observed a reduction of 52 % of the standard deviation of manual spot-weld placement when using augmented reality visual cues. This reduction demonstrates the benefit of having an AR projection system on the production line as opposed to not having one. The visual cues helped to identify spot-weld locations quicker and has the potential to be used as a training tool for new operators or new vehicle types. The SAR projection system can be positioned at any manual production station for spot welding, welding, adhesive application, and inspection.

Schwerdtfeger et al. [18] explored the use of laser projectors as an alternative to Head-Worn Displays for Industrial Augmented Reality applications. They used two scenarios to gather practical experiences with AR laser projectors: quality assurance and maintenance. They concluded that laser-based augmentations have much potential and they said to be in the process of installing, evaluating and further developing the system in the context of real industrial applications.

Otto et al. [19] presented a scalable, interactive augmented floor surface in combination with a tangible tabletop hardware and a material zone planning software. The floor projection hardware was used for true to scale assembly station layout visualizations. The system was installed, introduced and piloted during on-site production planning workshops for a mid-size premium car. A preliminary evaluation found that by tendency, true to scale visualization using the interactive augmented floor surface supports the workshop participants to better estimate sizes, speeds and spatial relationships than on traditional desktop displays.

Sand et al. [20] presented a prototype that has many similarities with our concept, such as the frame holding the projector and the camera. "smARt.assembly" is a projection-based augmented reality (AR) assembly assistance system for industrial applications. This system projects digital guidance information such as picking information and assembly data into the physical workspace of a user. Compared to their previous prototype with smart glasses, the projection-based system seemed to be much more robust on changing light conditions. Furthermore, users working with the projection-based instructions were able to assemble products faster and with a lower error rate, compared to the system based on smart glasses.

In summary, the use cases of SAR found in the literature are the following:

- Spot-welding
- Quality assurance
- Maintenance
- Designing
- Assembly

Our prototype is intended to be installed on Manual Working Stations, where all these kinds of operations can be accomplished. Our work integrates the literature with a user study on the effectiveness of SAR in support of the operators while projecting technical instructions.

2.3 Research questions

The goal of our research is to create a technical documentation based on SAR. It should contain the same information contained in a paper manual, for example, text instructions and pictures, directly projected on the workbench. The added value of SAR is the possibility to locate with graphic signs on the real product, the parts involved in the task. Then, it is important to evaluate if this added value produces improvements in operator performance and if operators well accept this visualization modality.

From the presented works, we can say that the point of user evaluation of AR in the industrial domain is well addressed in the literature. Most of the works show that with AR it is possible to reduce times and error rates in task execution. The second section of the related works shows that the use of SAR in industrial scenarios is continuously growing, mainly due to brighter, lighter, and cheaper projectors. However, there are no works about user evaluation of an SAR system for technical instructions, versus a traditional mode of presenting instructions, based on printed manuals. It is not possible to transfer the results of user evaluations on traditional AR to SAR since most of the works in section 2.1 make use of 3D CAD models that are not displayable in an SAR interface.

Then, also considering the increasing relevance of SAR technology in the industrial contest, we felt crucial to make such evaluation. Therefore, in this work, we formulated these research questions:

1) Are SAR conveyed technical instructions more effective than paper ones?
2) Is SAR well accepted by users as technical guidance compared with a paper manual?

3 Material and methods

To compare the two instruction modes (hereafter, we call them Paper and SAR), we conducted a mixed design experiment evaluating user completion time and error rate, and their ratings. In both the approaches, a within-subjects experiment was carried out to test our hypotheses.

As regards the first research question, we formulated the hypotheses *(H1) SAR system will significantly reduce the amount of time to complete a set of maintenance tasks, compared to paper instructions,* and *(H2) SAR projection system will significantly reduce errors of a set of maintenance tasks, compared to paper instructions.* As regards the second research question we formulated the hypothesis *(H3) SAR projection system will significantly improve user acceptance.*

3.1 The system

We used the SAR workbench (Fig. 1) presented in [12] with the following technical specifications:

- A light frame to be clasped on a normal workbench of a Manual Working Station: working volume 1200 mm (L) x 1000 mm (D) x 600 mm (H).
- A DLP projector Benq W1080ST+ mounted on the frame.
- An industrial camera Imaging Source DFK 23U445.
- A turntable where the product to be assembled/maintained is fixed.
- The optical tracking is based on fiducial markers that are glued on the turntable.
- An additional lighting system is provided, to have a uniform lighting on the markers.
- A joystick accomplishes the content navigation.

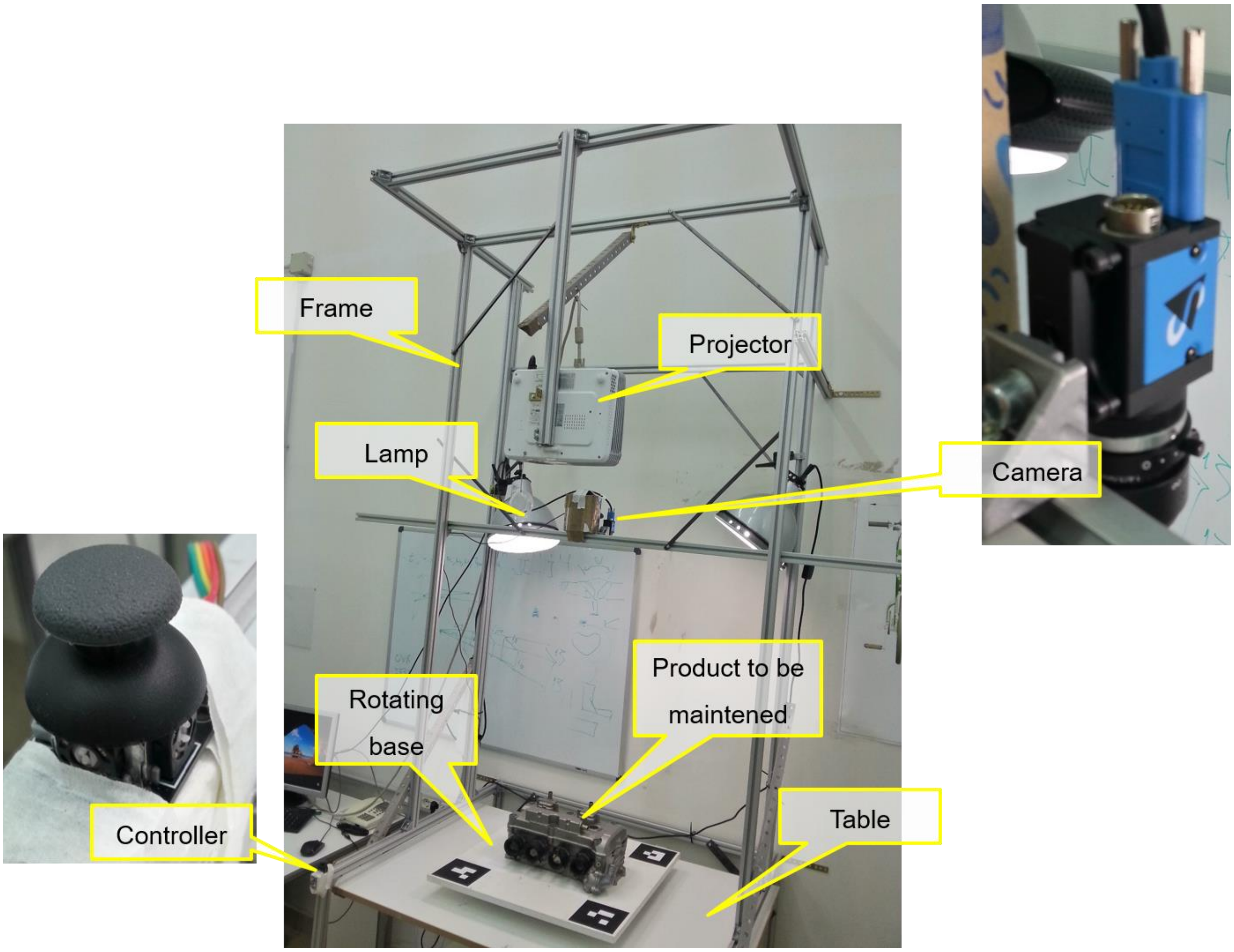

Fig. 1 The prototype of the SAR workbench used in the experiment

Further details of the SAR workbench, as well as the software architecture, can be found in [12].

In a previous study, we successfully reorganized, according to a tree-like structure, the instructions for a maintenance procedure in a digital manual [18]. In this tree, each level gives a complete description of the procedure, but as the user moves from the root node towards the leaves, the description of each step is decomposed in more sub-steps with a growing level of detail.

This structure allows technicians a fast and effective browsing of instructions ─ by skipping well-known details and by accessing specific information only if necessary.

The Graphical User Interface of the SAR system projects the tree structure on the left side of the workbench surface, as the bullets of a multilevel bulleted list. The bullet corresponding to the visualized step has a different color (acting as a bookmark); meanwhile, the graphic signs (such as arrows and circles) and a textbox with instructions are projected on the object and the workbench surface respectively.

3.2 Participants

A total of 16 voluntary participants (all males) were recruited among engineering students at Politecnico di Bari, using convenience sampling. The average age was 24.6 (min 22, max 32, SD = 2.17). We interviewed the subjects about their personal experience in maintenance operations: 14 participants had previous experience; 2 had no experience, half of the participants had previous experience with maintenance manual instructions, 14 participants were novices to AR and computer based maintenance guidance systems.

The participants in this study were all engineering students and therefore, highly interested and favorable to modern technologies. Furthermore, only half of them had previous experience with maintenance instructions. Considering this background of our participants, we designed an experiment with very basic tasks so that the experience and the motivation of the participants would not affect the results.

3.3 Procedure

Participants were assigned to both treatments, paper and SAR one, using a Latin square design. Then, we had eight participants performing first the paper mode and then the SAR mode and the other eight vice versa. They were told to complete each task as quickly and as accurately as possible. Each participant was allowed to familiarize with the system for 10 minutes before the test. This training phase helped the participants to get accustomed with the user interface ─ the controls to navigate the tree of instructions and the visual and textual information given by the system. At the end of the training phase, an experimenter checked that the participant was able to use the system easily.

We video recorded each user test. Completion time was measured by carrying out an offline analysis on these videos. We measured both the completion time of each task and the overall procedure. A human assistant supervised each test and checked for errors in real-time, using a notepad to register types and causes of mistakes. The assistant observed the user from a distance, without hindering her/his movements. After completing the test, users were asked to respond to a questionnaire to get subjective evaluations about the treatments.

We chose as a case study, part of the maintenance procedure of a Honda CBR 600 motorbike engine. We arranged a task sequence based on the maintenance procedure for the camshafts inspection. The operations used in the test include common and crucial maintenance tasks: part localization, components identification, sequences identification.

The sequence of the tasks is the following:

- Task 1. Cylinder head cover removal: pull out six bolts in no particular order and remove the cover;
- Task 2. Cam chain guide removal: pull out two bolts in no particular order and remove the guide;
- Task 3. Removal of the exhaust and intake camshafts and their holders: pull out eighteen bolts in a specific order and remove the camshafts in a given order;
- Task 4. Assembly of the exhaust and intake camshafts in a specific order and a proper position;
- Task 5. Assembly of the exhaust and intake camshafts holders: assemble the camshafts and insert eighteen bolts in a specific order;
- Task 6. Cam chain guide assembly: insert the guide and two bolts in no particular order;
- Task 7. Cylinder head cover assembly: insert the cover and first two bolts, then the other four.

We designed an experiment that could be the least affected by users' skills and dexterity in workshop operations. For this reason, we simplified the un/screw operations by replacing the original bolts with plain unthreaded ones that only needed to be pulled out/inserted from/into their slots. We added an instruction about the correct position of the lobes of two cams for the proper installation of the camshafts (Task 4). For this reason, we separated this task from that of the assembly of the holders. We prepared two similar sequential procedures for paper and SAR instructions, available in Appendix. The instructions about the identification of a component (e.g. a bolt), in the SAR mode, are given red "coloring" the interested area, as can be seen in Fig. 2.

We considered tasks with different levels of difficulty. We used the definition of task difficulty made by Kantowitz [19]: "task difficulty increases with the capacity investment needed to obtain a specified level of performance." In our test, the level of performance desired is that of a skilled operator doing the task. Task difficulty is an intrinsic property of a task, and it must not be confused with task complexity, which is related to instruction mode. The complexity, according to Kantowitz [19], refers to "the (hypothetical) mental system architecture used to perform a task." As additional internal stages or processes are required, task complexity increases.

In our experiment, we evaluated, in a range from 1 to 3, difficulty and complexity indices associated with our seven tasks with a think-aloud procedure in a team of maintenance experts.

For example, we can observe difficulty and complexity for Task 1 and 3:

	Difficulty	Complexity	
		Paper	SAR
Task 1	*	*	*
Task 3	***	***	*

Task 3 requires the removal of eighteen bolts in a given order. It is more difficult than Task 1, which requires the removal of six bolts in no particular order. As regards complexity, Task 3 is more complex to accomplish with the paper manual than with the SAR because the number of mental processes required to execute the task increases. In the paper, the user has to read the text instruction, to make a mental match of the camshaft holder and its printed image, and to remember the progressive number. With SAR, the user has only to read the instruction (less text) and to localize the red circle projected on the engine. On the contrary, Task 1, presents the same low complexity in paper and SAR instruction mode.

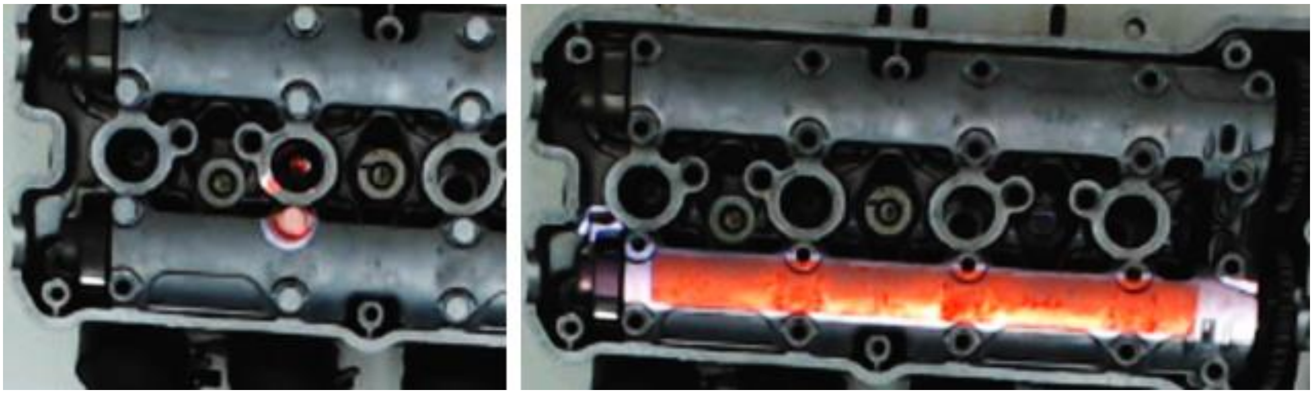

Fig. 2 Colored graphic signs used in the SAR mode to indicate a bolt (left) and a camshaft holder (right) to be removed

Table 1 Independent and dependent variables of the experiment

INDEPENDENT VARIABLES		
Participant users	16	16 males, mean age 24.6
Instruction Modes	2	Paper, SAR
Tasks	7	Dis/assembly tasks, as described in the previous section
Total trials	**224**	16x2x7
DEPENDENT VARIABLES		
Completion time	time (in seconds) spent for the execution of each task and the overall procedure	
Error	wrong task completion	
Users rating	votes assigned by users in a 5 points Likert scale, for each instruction mode as regards ease of use, intuitiveness and global satisfaction	

3.4 Measures

The experiment's independent and dependent variables, collected for the subsequent statistical analysis, are shown in Table 1. We used the following error rate definition:

$$ER\% = \frac{n.errors}{n.targets} \cdot 100$$

The *n.errors* is the sum of all the participants' errors observed for each task. The *n.targets* is the maximum number of errors that a user could make for each task, multiplied by the number of the participants that performed the experiment. For example, for Task 5, the possible errors are:

- Wrong assembly of the exhaust camshaft;
- Wrong assembly of the intake camshaft;
- Wrong assembly of a screw (for all the eighteen screws).

Then, the maximum number of errors that each user could make for Task 5 is 20 (1+1+18); multiplying this number by the number of participants (16), we have that *n.targets*=320 for Task 5.

4 Analyses and results

We used two separate statistical models to analyze the effects of the instruction mode and the task type on time and error rate.

4.1 Completion time

Completion time was analyzed using the ANOVA. Instruction mode and task-type were modeled as fixed effects. Participant ID was modeled as a random effect. In Task 6 one user had a very bad performance due to an error in the accomplishment of the previous task. This bad performance resulted in a strong outlier (i.e. distance from the third interquartile greater than three times the interquartile distance). Thus we decided to neglect the completion times of this user for the statistical comparison of this task and the overall procedure.

To compute the ANOVA, we initially had to verify normality and homoscedasticity. If both were verified, we could proceed with a classic homoscedastic parametric ANOVA. Otherwise, we had to perform other tests.

For the normality test, since the size of the group we wanted to analyze was limited (N=16), we chose to use the Shapiro-

Wilk test. All samples positively passed normality and homoscedasticity tests.

We conducted a planned pair-wise comparison of completion time between instruction modes for each task and the overall procedure (Table 2). The results allow us to confirm the null hypothesis H1. Comparing the means, for these operations, we found a completion time improvement with the SAR mode over the Paper mode. For the overall procedure, we found a significant [$F(1,30)=22.973$, $p<0.001$] reduction of 20.3% of completion time.

As to the substeps, we found a significant [$F(1,30)=51.247$, $p<0.001$)] reduction of 32.5% of time completion for the Task 3, and a significant [$F(1,30)=14.207$, $p=0.001$)] reduction of 21.6% for the Task 5.

Table 2 Statistical analysis for the completion time

Task	One-way ANOVA		Mean completion time	
	F	p	Paper Mode	SAR Mode
Task 1	0.024	0.879	36.9 s	37.4 s
Task 2	1.723	0.199	23.3 s	20.0 s
Task 3	51.247	<0.001	**190.4 s**	**128.6 s**
Task 4	1.987	0.169	95.1 s	82.4 s
Task 5	14.207	0.001	**201.2 s**	**157.7 s**
Task 6	4.179	0.050	24.3 s	19.3 s
Task 7	3.662	0.065	48.4 s	41.3 s
Overall	22.973	<0.001	**610.9 s**	**486.7 s**

4.2 Error rate

To make statistical analyses about the influence of instruction mode on the accuracy of the operations, we grouped the error data of all the users involved, for each task type. Then, for each task, we computed the error rate as defined in Section 3.4. We used the method of "nx2 contingency tables" to make statistical inference.

Comparing the error rates of the experiment tasks (Table 3), we observed an error rate reduction with the SAR mode over the Paper one.

Table 3 Statistical analysis of error rates

Task	Chi-squared test		Error rate	
	χ^2	p	Paper Mode	SAR Mode
Task 1	0.000	1.000	0%	0%
Task 2	0.000	1.000	6.25%	6.25%
Task 3	21.646	<0.001	**5.97%**	**0%**
Task 4	8.085	0.004	**20.00%**	**2.08%**
Task 5	5.530	0.019	**3.75%**	**0.94%**
Task 6	0.368	0.544	6.25%	12.50%
Task 7	3.865	0.049	**43.75%**	**12.50%**
Overall	33.518	<0.001	**7.03%**	**1.17%**

This result allows us to confirm the null hypothesis H2. Instruction mode has a significant effect on the overall procedure [$\chi^2(1)=33.518$, $p<0.001$]. As to the specific tasks, we found a significant difference for Task 3 [$\chi^2(1)=21.646$, $p<0.001$], for Task 4 [$\chi^2(1)=8.085$, $p=0.004$], for Task 5 [$\chi^2(1)=5.530$, $p=0.019$], and for Task 7 [$\chi^2(1)=3.865$, $p=0.049$]. For all the other tasks, we did not find a significant difference between error rates for the two instruction modes.

Error! Reference source not found. reports a comparison of the results for the single tasks with their difficulty index and their complexity, as defined in Section 3.3.

4.3 Subjective evaluation

The post-experiment questionnaire featured five-point Likert scale questions (1 = most negative; 5 = most positive) to evaluate ease of use, satisfaction level, and intuitiveness for each Instruction Mode. The summary results from these ratings are reported in Fig. 3.

Medians of the ratings for SAR mode were always higher (5) than Paper mode (3 for ease of use and intuitiveness, 2.5 for satisfaction) for any of the three characteristics.

Table 4 Comparison of task difficulty, complexity and performance improvement

Task	Difficulty	Complexity		Significantly different?	
		Paper	SAR	Completion time	Error rates
Task 1	*	*	*	NO	NO
Task 2	*	**	*	NO	NO
Task 3	***	***	*	YES	YES
Task 4	***	***	**	NO	YES
Task 5	***	***	*	YES	YES
Task 6	*	**	*	NO	NO
Task 7	**	***	*	NO[1]	YES

[1] towards significance (p=0.065)

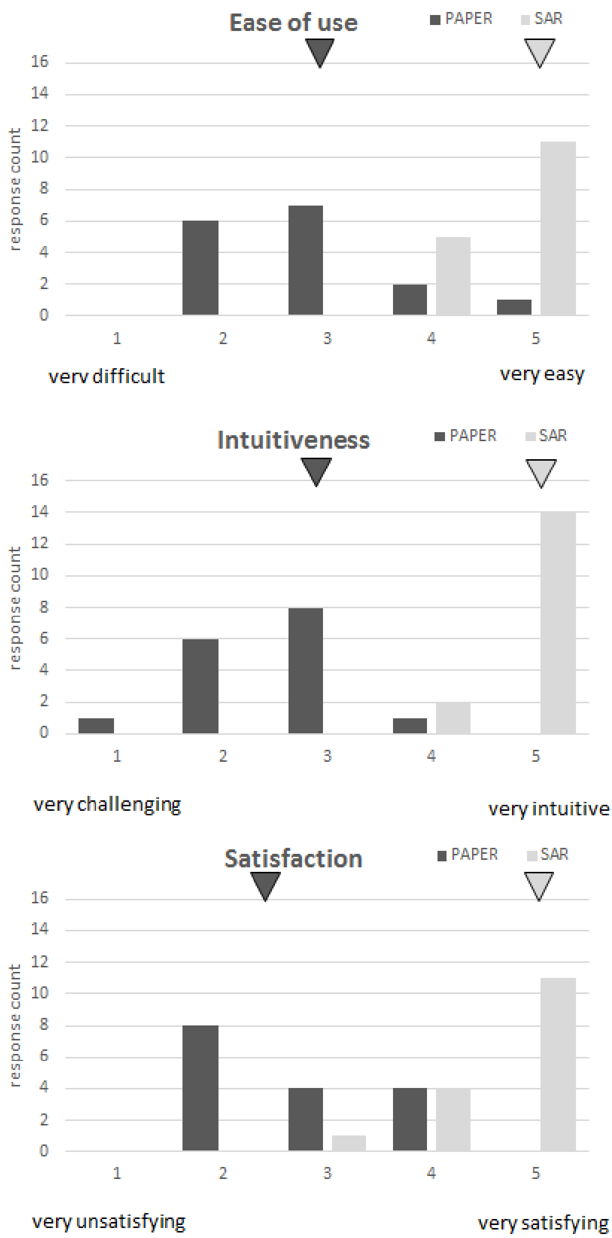

Fig. 3 User ratings about ease of use (top), intuitiveness (middle), satisfaction (bottom). Median values for each condition are shown as triangles

5 Discussion and conclusions

The results showed that SAR presentation mode is significantly better than paper one in completion times (reduction of 20.3% in overall completion time) and error rates (83.3% fewer errors with the SAR mode) confirming H1 and H2. Subjective evaluation supported H3 (at least 2 points higher for SAR mode), confirming good user acceptance of SAR technology for conveying technical instructions.

Tasks with low difficulty (tasks 1, 2 and 6) show no significant difference ─ both for completion times and for error rates.

Tasks with high difficulty (tasks 3, 4, 5 and 7) show a significant difference in error rates. Tasks with high difficulty show a significant difference for completion times only if there is a substantial reduction in complexity due to SAR.

Tasks 3, 5 and 7 require the understanding of a correct sequence of the bolts. Indeed, using the paper manual, either the mental workload associated with these instructions is high if users tried to memorize the sequence of the bolts, or the cognitive distance is high if users switched from information space (the manual) to physical space (the engine) for every bolt or both. The SAR highly reduces the complexity of these tasks because the technical information is conveyed illuminating the bolt to be pulled out/inserted. With the SAR, we have then two great benefits: 1) the reduction of the mental workload associated with a task because only the task-relevant information is displayed; 2) the reduction of the cognitive distance because the information space and the physical space coincide. This result is consistent with what suggested and proved by Kim and Dey [20].

In task 4 the reduction in complexity is lower than in the other tasks. Task 4 shows contrasting results: there is a significant and relevant decrease of the error rate but the difference in the completion times is not significant. Task 4 is also a difficult task, but the textual information is the same for paper and SAR, and therefore the time needed to read and understand the instruction is similar. However, SAR provides explicit component identification (green illumination of the portion of the engine to control), thus reducing error rates.

From these results, we can conclude that the use of SAR brings more advantages for difficult tasks than for simple ones. The main advantage of SAR is related more to the reduction of error rates than to completion times. These results were never found before in the literature for SAR, thus supporting the motivation for our research.

For traditional AR, in which 3D CAD models are used for displaying information, we found works where AR reduces both times and error rates and works showing only error rate reduction. Our result agrees with what found by Tang et al. [14]: in their experiments, AR does not appear to have an advantage in time of completion comparing with other traditional media; nevertheless, they observed a strong reduction of error rates. The tasks in our and their experiment are very similar, based on the identification of a specific part and its positioning in a specific position. However, we achieved this result without using the CAD model of the assembled parts (screws), but just that of the engine used as occlusion model and as a projection mapping reference geometry, with a strong effort reduction in the authoring phase. Indeed, we experienced authoring times much shorter in modeling and positioning of the colored graphic signs than in modeling and animating virtual screws.

Thus, we can conclude that SAR, similarly to traditional AR, always ensures low error rates and consequently guarantees operator accuracy. This result is important because it is in line with the objectives of Industry 4.0 and supports the role of AR as a key technology for a smart factory. Our industrial partners always considered overriding the reduction of the errors made by the operators and optional the reduction of times.

The result of this work for maintenance dis/assembly operations should be read together with what found in the literature for other manufacturing processes, such as data visualization of CNC machines [21], spot-welding operations [17], human-robot collaboration [22], and other manufacturing processes. Therefore, we can feel that SAR technology can be integrated shortly into industrial processes and product lifecycle. In particular, the SAR prototype presented in [12] could be, with further improvements, a good candidate for a future introduction of SAR in a smart factory. However, the advantages of SAR found with our validation are just the starting point to be sure of the path taken. Other problems remain open such as the authoring of contents, the tracking, the usability, the interface design. In the authors' view, when all these issues will be addressed, industries will accept the introduction of SAR in their practices.

The SAR solution proposed and tested can be used for both training new maintenance operators and assisting operators in ordinary maintenance. In fact, we designed a multilevel tree-like structure of the procedure-instructions. It allows regular technicians a fast and effective browsing of instructions, by skipping well-known details and by accessing specific information only if necessary. While for new operators, there is the possibility to provide further detailed information to learn new procedures. In our work, the information detail is high because both text, images and graphic signs were used and users were asked to browse all the procedure steps.

Even if the case study used here is very basic, there are some tasks, as Task 3 and Task 5, where the mental workload is high because a dis/assembly order should be memorized. In these cases, SAR is helpful also for experienced maintenance operators, who usually can perform the procedures even without the support of instructions because they learned them over time. Furthermore, in the age of Industry 4.0 manufacturing is mainly based on mass customization. Thus, even experienced operators could work on many various products or versions of the same product, and they could not memorize all the relative procedures.

However, in this study, we did not consider as a variable the experience of operators, as well as the learning effect due to the repetition of a procedure at different times, or the possible fatigue of operators using SAR. In a follow-up study, it would be interesting, to evaluate the effect of these variables on user performance with SAR. We aim to test our SAR system in our industrial partners' facilities and carry out some pilot studies in a real scenario with actual workers.

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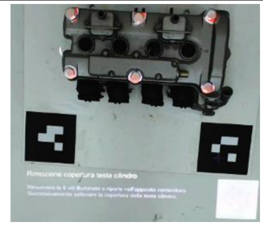
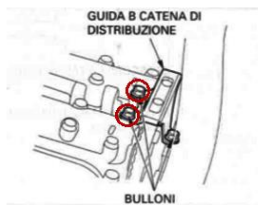
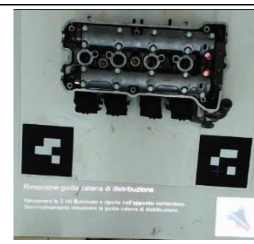
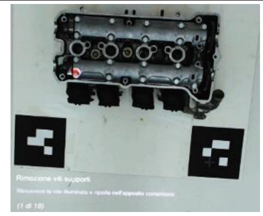
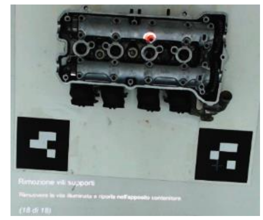
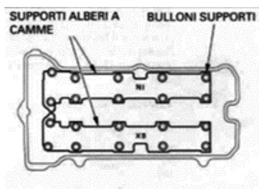
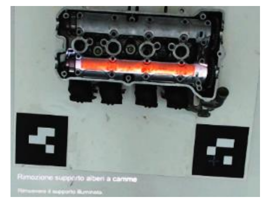
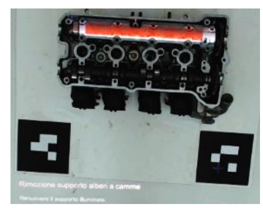
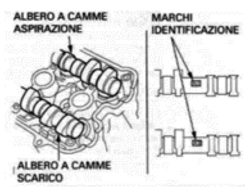
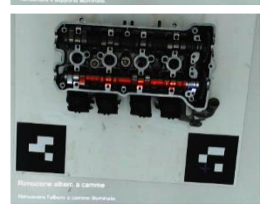
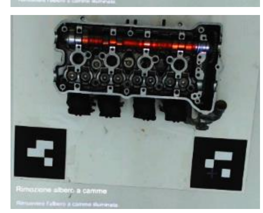
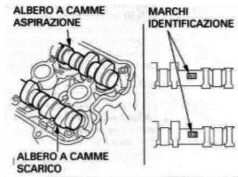
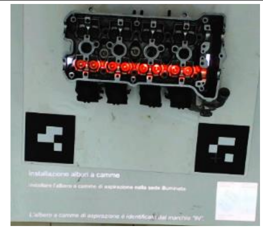
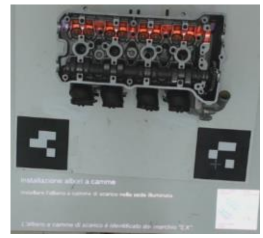
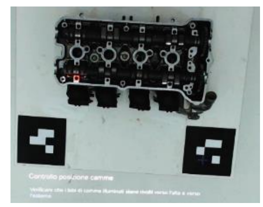
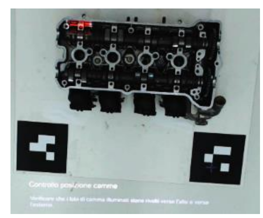
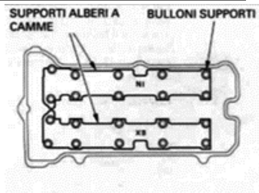
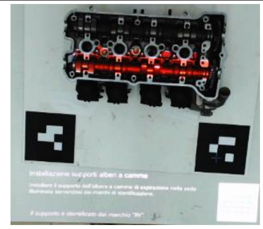
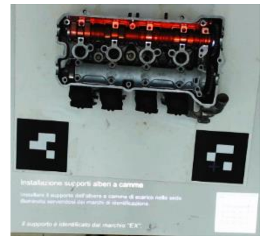
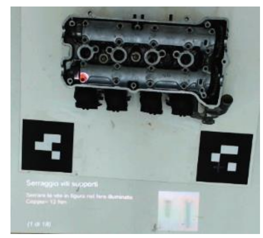
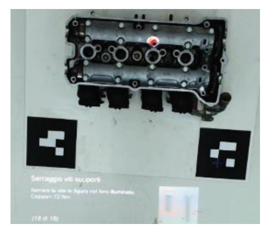
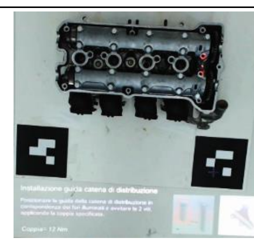
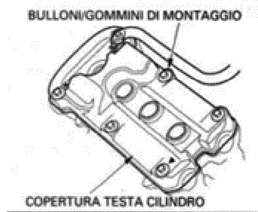
6 Appendix

	Paper mode		SAR mode	
	Textual content	**Visual cues**	**Textual content**	**Visual cues**
Task 1	• Remove the 6 screws of the cylinder head cover and place them in the container; • Lift the cylinder head cover.		• Remove the 6 illuminated screws and place them in the container; • Lift the cylinder head cover.	
Task 2	• Remove the 2 screws of the distribution chain guide, and store them in the container; • Remove the distribution chain guide.		• Remove the 2 illuminated screws and place them in the container; • Lift the cylinder head cover.	

	Paper mode		SAR mode	
	Textual content	**Visual cues**	**Textual content**	**Visual cues**
Task 3	• Remove the screws of the intake camshaft holder, identified by the mark IN, in the following order and store them in the container: 1-8-3-9-2-4-7-5-6;		• Remove the illuminated screw and place it in the container. (1 of 18);	
	• Remove the screws of the exhaust camshaft holder, identified by the mark EX, in the following order and store them in the container: 8-9-3-2-1-7-5-4-6;		• Remove the illuminated screw and place it in the container. (18 of 18);	
	• Remove the intake camshaft holder, identified by the mark IN.		• Remove the illuminated camshaft holder;	
	• Remove the exhaust camshaft holder, identified by the mark EX.		• Remove the illuminated camshaft holder;	
	• Remove the intake camshaft, identified by the mark IN.		• Remove the illuminated camshaft;	
	• Remove the exhaust camshaft, identified by the mark EX.		• Remove the illuminated camshaft.	

<table>
<tr><th rowspan="2"></th><th colspan="2">Paper mode</th><th colspan="2">SAR mode</th></tr>
<tr><th>Textual content</th><th>Visual cues</th><th>Textual content</th><th>Visual cues</th></tr>
<tr><td rowspan="4">Task 4</td><td rowspan="4">• Install the camshafts on the cylinder head with the cam lobes # 1 facing upwards as shown in the figure.
• NOTE: Install the camshafts in the correct position using the identification marks:
• “IN” – intake camshaft
• “EX” – exhaust camshaft
• Install the intake camshaft.
• Install the exhaust camshaft.
• Check that the bearings are aligned with their seats.</td><td rowspan="4">
</td><td>• Install the intake camshaft in the illuminated seat.
The intake camshaft is identified by the mark “IN”;</td><td></td></tr>
<tr><td>• Install the exhaust camshaft in the illuminated seat.
• The exhaust camshaft is identified by the mark “EX”;</td><td></td></tr>
<tr><td>• Check that illuminated cam lobes face upwards and outwards;</td><td></td></tr>
<tr><td>• Check that illuminated cam lobes face upwards and outwards;</td><td></td></tr>
</table>

	Paper mode		SAR mode	
	Textual content	**Visual cues**	**Textual content**	**Visual cues**
Task 5	• Install the camshaft holders in the correct position using the identification marks: • "IN" – intake camshaft holder • "EX" – exhaust camshaft holder • Install the intake camshaft holder. • Install the exhaust camshaft holder.		• Install the intake camshaft holder in the illuminated position using the identification mark: • "IN" – intake camshaft holder	
			• Install the exhaust camshaft holder in the illuminated position using the identification mark; • "EX" – exhaust camshaft holder	
	• Install the screws of the intake camshaft holder, in the following order: 1-8-3-9-2-4-7-5-6;		• Insert the screw in the illuminated hole (1 of 18);	
	• Install the screws of the exhaust camshaft holder, in the following order: 8-9-3-2-1-7-5-4-6.		• Insert the screw in the illuminated hole (18 of 18).	
Task 6	• Install the distribution chain guide; • install the two screws of the distribution chain guide.		• Place the distribution chain guide in correspondence with the illuminated holes and install the two screws.	

	Paper mode		SAR mode	
	Textual content	**Visual cues**	**Textual content**	**Visual cues**
Task 7	• Install the cylinder head cover. • Install the special screws of the cylinder head cover • Caution: Install first the screws in the holes marked by “Δ.”		• Install the cylinder head cover as in figure;	
			• Insert the screw in the two illuminated holes. (2 of 6);	
			• Insert the screw in the four illuminated holes. (6 of 6);