Augmented Reality for Remote Assistance (ARRA)

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Abstract Augmented Reality (AR) reduces the technicians' cognitive effort mainly resulting in both time and error rate reductions. Still, its application in remote assistance has not been fully explored yet. This paper focuses on understanding the benefits of providing assistance to a remote technician through AR. Augmented Reality for Remote Assistance (ARRA) has been designed and developed for local novice maintainer to request assistance and communicate with a remote expert. The remote expert can manipulate virtual objects, which are then overlaid on the real environment of the novice maintainer. ARRA has been tested with the help of 60 participants. This involved performing an assembly/disassembly operation on a mock-up of a piping system. The participants were remotely assisted through ARRA or video-call. Quantitative spatial referencing error data has been collected. The results showed a 30% improvement in terms of spatial referencing when utilising ARRA as remote assistance support as opposed to video-call. Future studies should investigate into quantifying the improvements due to other factors involved in remote assistance, especially language barriers and connectivity issues.

Keywords: Augmented Reality, digital engineering, maintenance, remote assistance, spatial referencing

1 Introduction

The increasing complexity of industrial machinery due to the constant push for improvements in productivity and reliability of industrial facilities has provided a flourishing ground for research and innovation [1]. Internet of Things, Digital Engineering, Smart Factory, Virtual Reality, Digital Twins, Augmented Reality (AR) are only a few of the words utilised today for describing approaches and technologies which could enhance and support the fourth industrial revolution and take us to the nowadays well-acknowledged Industry 4.0 [2]. In this study, we explore the utilisation of AR for Remote Assistance (RA) applications in maintenance. Several definitions of AR are provided in the academy. The first and most widely recognized one has been provided by Azuma in 1997 [3] and restated in 2001 [4]: "AR supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world", moreover an "AR system has the following properties: combines real and virtual objects in a real environment, runs interactively and in real-time, registers real and virtual objects with each other's".

Maintenance, Repair, and Overhaul (MRO) operations have a big impact on the lifecycle of industrial equipment [5] and strongly rely on the maintenance technician's expertise [6]. In this scenario, AR technology for remote assistance (RA) can potentially allow the "de-skilling" of the remote maintenance operations and, at the same time, improve flexibility and costs of maintenance [7]. The flexibility in the maintenance scenario is the capability of performing MRO operations without specific skill-requirements, location constraints, and effective with unexpected events [8]. The cost would be directly affected by avoiding the need for time consuming and expensive maintenance training as well as traveling [9]. It is not uncommon that machinery vendors are required to provide assistance in remote locations because their technicians are better trained to perform MRO on the vendor's product (industrial machinery, tooling, instruments). Similar maintenance dynamics may occur also within different departments of the same company. To provide such benefits, the ARRA tool should overcome three main limitations of current RA technologies based on voice and video call support as follows [10]:

1) Spatial referencing – identifying the correct location and orientations of the object in space
2) Communication barriers – language describing actions can be vague and ambiguous
3) Connectivity issues – relying on 4G or Wi-Fi internet connection can affect RA

This paper focuses on improving spatial referencing through the utilisation of AR for RA. The authors developed an AR approach that puts in communication two technicians situated in different locations: the expert and the novice. The novice here refers to the maintainer who does not sufficiently know how to perform the maintenance task and requires support from the expert (e.g. from the vendor). The AR approach has been called ARRA: Augmented Reality for Remote Assistance. It is based on the assumption that the AR system can recognise and track the objects in the Field of View (FOV) of the novice and that the CAD models of the objects for MRO are available. ARRA allows in execution-time order: 1) the novice to request assistance, 2) the expert to visualise virtually on his real environment, the objects to be MRO, 3) the expert to manipulate the virtual object to build a step-by-step MRO procedure 4) the novice to visualize the step-by-step MRO procedure and 5) the expert to monitor the progress of the MRO procedure. This paper is structured as follows. Section 2 provides the research background and motivation. Section 3 describes ARRA: how it works and its technical development. The detailed methodology for ARRA's validation is described in Sect. 4. It includes the description of the case study utilised (Sect. 4.1) and the quantitative test design (Sect. 4.2). Analysis and results are reported in Section 5. Finally, the discussion of the results and the conclusions and future works are proposed in Section 6 and 7, respectively.

2 Background

AR for MRO applications has been widely explored by academics and the benefits that AR technology could bring to the industrial environment are mainly: time reductions, error reductions, cognitive load reduction, training reduction, cost reduction [11–13]. AR applications specific for RA in maintenance, on the other side, have been investigated and proposed only by the 8% of the academic studies of AR in maintenance [11]. It is worth to mention that some studies, rather than talking about "remote assistance", utilise the words "tele-presence", "tele-assistance" or "tele-maintenance" to indicate the capability of providing support to remote operators through the utilization of AR or other technologies (VR, the Cloud, Computer) [14–16]. Reference [17] in 2014, proposed a client-server AR system which allows the remote expert to overlay symbols and written instructions over the real internal combustion engine where a remote novice maintainer is carrying out the maintenance operation. This application has been designed for increasing customer satisfaction, cut costs, and allow rapid intervention always considering low connectivity. Reference [18] in 2015, attempted to utilise Mobile Internet Devices (MIDs) such as smartphones to remotely acquire data on a machine (equipped with its electronics and monitoring sensors) and apply corrective actions if required. The corrective actions can be suggested by the remote manufacturer or maintainer by means of AR annotations and/or directly modifying the machine parameters. This method requires a gateway architecture that is not always available and applicable only on heavily electronics equipped machinery. Reference [18] in 2015, developed and compared three remote support systems: Sketch3D, Point3D, and Demo3D. The utilisation of Demo3D resulted in the shortest completion time of the assembly task selected in the study. The system enabled the remote expert to manipulate a virtual object through the utilisation of a Head-Mounted Display (HMD) and a tracked mouse. The final configuration of the virtual replica was then overlaid on the real environment of the novice remote maintainer who could take advantage of the invariant spatial referencing of AR and verify the proper alignment of the real objects. Nevertheless, it did not consider this solution applicable to complex maneuvers. In 2017, another example of RA through AR that connects the cloud-based system to the assembly plant was demonstrated [19]. The MTBF of the machines to be maintained was calculated through an automated analysis of the maintenance logs and sensors data. If there is a requirement for preventive maintenance, the technician on the plant can then request assistance. The maintenance department is able to build a maintenance report which includes AR scenes, animations, and instructions. These are generated through a "smart dis/assembly algorithm". More specifically, the animations were built through the analysis of the physical constraint on CATIA. For instance, once the object to be maintained has been identified, the CAD model was automatically analysed on CATIA and the components' DOF were evaluated. If a component can move in at least one direction without colliding with other components, it can be disassembled. This solution overcomes communications barriers and provides an interesting attempt to automate, and hence, solve one of the main issues of the implementation of AR in maintenance: the AR contents creation [20–22] . Still, we believe it is slightly too simplistic. The solution was not only unable to provide different solutions for the same problem, but also it did not consider unpredicted events and did not take advantage of the human experience which is essential in maintenance [6].

The AR solutions for RA described testifying the effort in pushing forward the utilisation of AR. Still, it is not clear how much benefit could we expect from its implementation. For this reason, in this paper, the authors will attempt to quantify the expected spatial awareness benefits resulting in the utilisation of AR for RA.

3 ARRA

Augmented Reality for Remote Assistance (ARRA) is our proposed approach for overcoming spatial referencing issues, which affect current RA technologies: video/voice all support, VR, and AR. As anticipated, ARRA is based on two assumptions:

1) The system can recognise and track the object in the FOV of the remote novice maintainer
2) The CAD models of the objects to be maintained are available.

The authors consider the assumptions plausible due to the recent advancement in image processing, depth sensors, and CAD modelling [11, 23]. Figure 1 reports a schematic concept of how ARRA works, what is the data flow, and what are the main processes involved. On the left, the remote novice maintainer carries out a maintenance operation without having the required knowledge. The initial current status (components positions and orientations) of the object to be maintained is sent to the remote maintainer. The remote maintainer can visualise the objects and virtually manipulate them. He performs the maintenance operation on the virtual objects. This is sent back to the novice maintainer that visualises it overlaid on the real objects. The novice can then follow the steps of the procedure while the expert is monitoring the movements of the objects (3*) since the system is continuously sending the objects' current status. At any stage of the assistance, both the expert and the novice can request to restart from process 1*. This may occur in two main occasions:

1) The novice is not able to follow the overlaid procedure (2*)
2) The expert has noticed something wrong in the movements of the object real-time (3*)

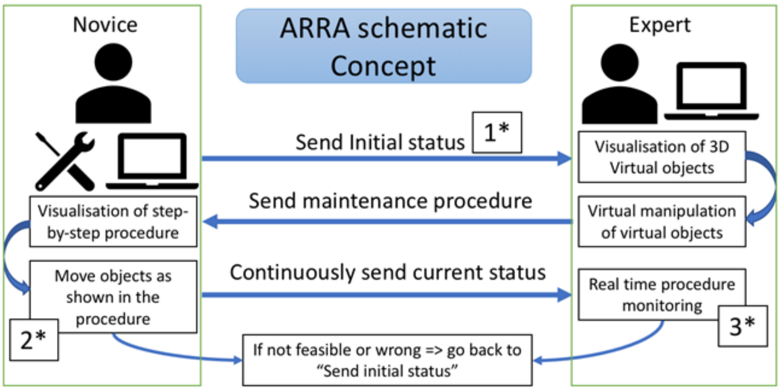
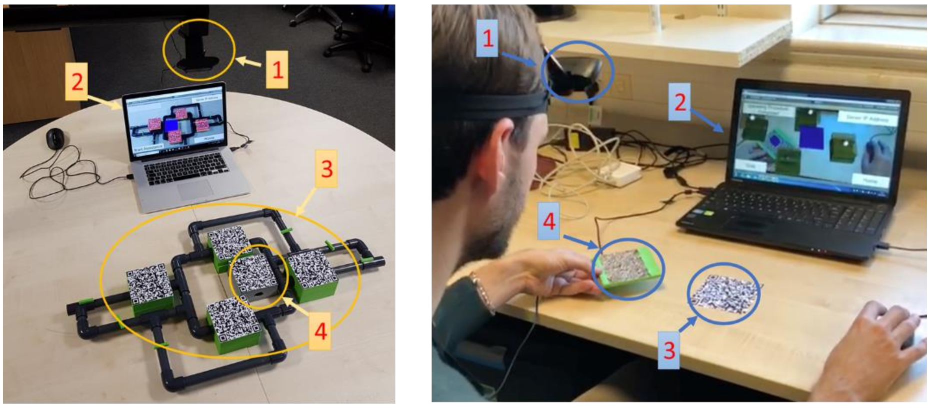


Fig. 1. ARRA schematic concept and functionalities

The key to improving the spatial referencing with respect to video/voice supports lies in the AR technology and the utilisation of the relative positions of the objects with respect to the anchor marker located in both the novice and the expert environments. In order to provide a better understanding of how ARRA works, the following sections will show a practical example in Sect. 3.1 and the technical development details in Sect. 3.2.

3.1 ARRA: A Practical Example

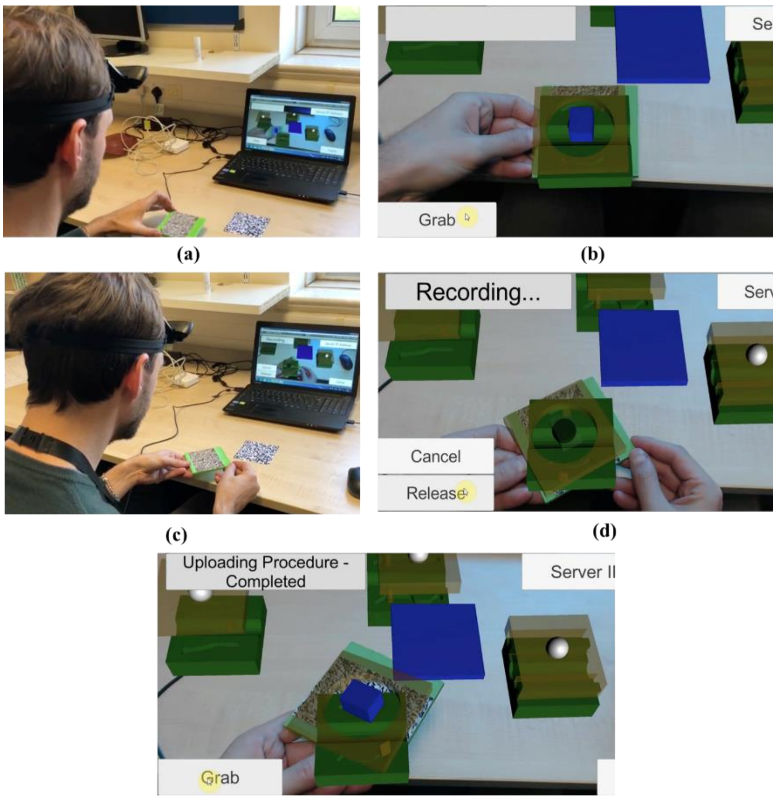
This section reports a practical example of how ARRA works. The pictures utilised for explaining ARRA have been taken during the validation tests and are utilised here to better explain to how ARRA allows AR communication between the novice and the remote expert maintainer, what information is transferred and how the novice maintainer becomes able to perform a maintenance operation through ARRA. The validation tests and the case study will be described in detail in Sect. 4.1. Two different environments are considered, for instance: the novice's shop-floor (Fig. 2a) and the expert's desk (Fig. 2b). The novice environment includes: 1) an RGB camera facing the working area, 2) a laptop/display 3) the object to be maintained and 4) the anchor marker. The image is taken from the novice's point of view. Four markers have been placed on the object to be maintained for easing the four components recognition for testing purposes. The expert environment includes: 1) an RGB camera facing the same direction as the expert, 2) a laptop, 3) the anchor marker and 4) the virtual manipulator tool. The latter is a real object which, once recognised as the virtual manipulator through its marker, allows to move and rotate virtual objects. It is worth to mention that, in both environments, the RGB camera and laptop could potentially be substituted with an HMD. The description of the example will now progress following the actual operation time sequence.



(a) (b)

Fig. 2. Novice and expert environments when utilizing ARRA

Firstly, the novice approaches the object to be maintained and understood he is lacking the knowledge necessary to carry out the maintenance operation, and thus, requests assistance through the UI of the ARRA application on the display.



(a) (b) (c) (d) (e)

Fig. 3. Expert scenario since receiving the request for assistance

The remote expert accepts the request for assistance and visualises the CAD models of the object to be maintained. More specifically, the four objects recognized by the novice's camera (Fig. 2a) and their position and orientation with respect to the novice's anchor marker, are

reproduced virtually on the experts' screen maintaining the same relative position with the maintainer's anchor marker (Fig. 3a). The expert understands what maintenance operation has to be carried out based on his/her expertise and places the virtual manipulator over the virtual component that has to be moved (Fig. 3b). Once he presses "Grab" (bottom left on Fig. 3b), the virtual component starts following the virtual manipulator movements. In Fig. 3c and Fig. 3d respectively, it was shown that the expert rotating the virtual manipulator and the virtual component rotating as well. Also, on the top left of the expert's screen (Fig. 3d), it is possible to see the current action performed by ARRA: "Recording". Please note, ARRA is not recording the video information but only the object positions and orientations through time by storing them locally. Once the expert has moved the object as required by the maintenance operation, he can select "Release" (bottom right in Fig. 3d) and the information recorded was uploaded on a cloud server database. The remote expert can now keep monitoring the movements of the real novice's objects through the virtual components on his/her display.
On the top left of the novice's display, the statement "Playing Procedure x" is shown (Fig. 4b). All the objects that are positioned and orientated correctly will be overlaid with its own CAD model colored in green. The component that has to be moved will be overlaid by its own CAD model in red. The latter is animated over the real one and moves as the expert has indicated previously (Fig. 3). The novice can now proceed and move the real object as indicated by the animation (Fig. 4c). In this specific case, the component has to rotate counterclockwise. Once the position and orientation indicated by the expert are reached by the real component, the overlaid CAD becomes green as shown in Fig. 4e. Both the novice and the expert can stop the procedure at any time through the specific UI button. For instance, the novice can stop it if, for any reason, he is not able to follow the animation; the expert should stop it if, while monitoring the movements of the virtual objects, he identifies an issue/mistake. It should be noted that independently from the orientation and position of the anchor marker with respect to the maintainer (novice and expert), the animations will always overlay on the correct object and move through the correct directions since these are "recorded" referencing to the anchor marker rather than the operator point of view. The novice should always address the correct component to be maintained and move it towards the correct direction and therefore we expect the spatial referencing to improve with respect to voice/video support technologies.

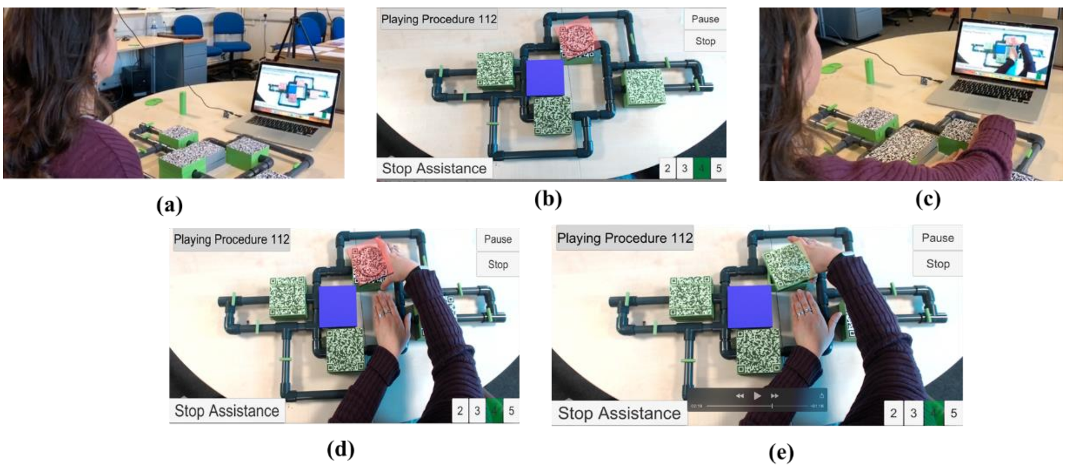


Fig. 4. Novice receives the remote support through ARRA

3.2 Technical Development

ARRA schematic concept (Fig. 1) and practical example have been described in the previous sections. ARRA approach formalises in an AR system constituted by hardware and software. The hardware utilised is commercially available and can vary from one application to another as long as suitable for allowing the actions described in Figure 1. The software has been developed specifically for this study and the hardware utilised in this study.

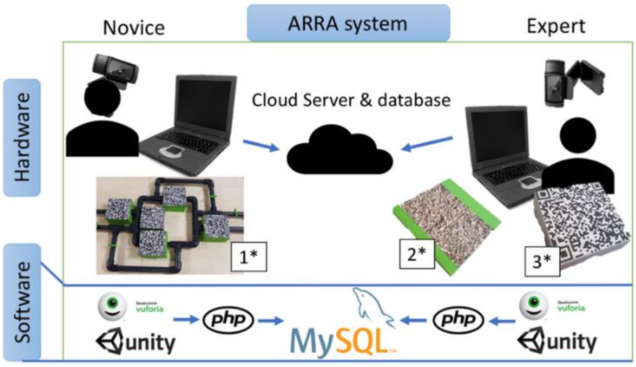


Fig. 5. ARRA System Architecture

Figure 5 shows the system architecture utilised in this project. The novice maintainer is on the left and the expert remote maintainer is on the right. Both of them were equipped with an RGB camera Logitech 1080, a laptop, and an anchor marker (3*, also described in sec 3.1). It is worth to mention that the RGB cameras' installation is different. The novice has it placed on his forehead through a strip while the remote expert has it installed facing the whole desk from a height of about 1.5 meters. This is because the novice should intuitively face the object to be maintained (1*) while the expert does not know a priori where the object is located with respect to the anchor marker and therefore, the whole desk needs to be in the FOV of the camera. Moreover, the remote maintainer also needs to have the virtual manipulator tool (2*): an object on which is placed the virtual manipulator marker. A different hardware solution utilising HMD and hand gesture sensors could have been used to improve the AR experience and take rid of the virtual manipulator hardware since the manipulation of the virtual objects could have been done directly through the recognised hands. Unfortunately, the use of HMD would have obstructed the validation tests by not letting the tests observers understanding what the tests participants were experiencing. The hand gesture recognition, on the other side, would have made easier the manipulation of the virtual object but required a more complex development without providing any advantage in quantifying the spatial awareness which is the scope of the study. The software for carrying on this study has been developed in Unity 3D and takes advantage of the Vuforia SDK for allowing the markers recognition. Rather than directly recognising the objects the authors decided to place markers (10x10 cm) on the objects for easing the validation test. The Unity application has been deployed for both Android and Windows. It has two user login kinds: 1) requesting assistance (novice maintainer), 2) providing assistance (remote expert). It is worth to mention that the software does not allow video communication. The two maintainers communicate only using AR as described in the practical example in Sect. 3.1. The server has been firstly located on a local machine by utilising XAMPP: open-source cross-platform web-server solution. Then it has been moved to a cloud server. The communication speed has not been affected due to the relatively small amount of information required to be exchanged to run ARRA. Only two tables of 8 columns are located on the server: 1) the Real Object DOF (RODOF), and 2) the Virtual Object DOF

(VOROF). Quantitatively, the novice writes only about 70 Bytes per half-second, per object in RODOF. It corresponds to 6 numbers: 3 for the position and 3 for the orientation of the object with respect to the anchor marker. The expert reads these 70 Bytes and writes about the same amount of data on VOROF when manipulating the virtual object. In summary, considering 5 objects, the uploaded data goes from about 140 Bytes to 1.5 KB per second which is low compared to video-call support (300 KB/s for no HD). The architecture proposed in this section/project is the one utilised for carrying out the validation tests and therefore complies with the test observation requirements.

4 Test Design and Methodology

ARRA has been described in Sect. 3, both schematically and through a practical example. Among the expected benefit in the utilisation of ARRA compared to video-call support for remote maintenance, the author intended to validate the improvement in terms of spatial referencing. To validate ARRA, the authors proceeded with the following three steps:

1) Quantification of the spatial referencing errors occurring when performing a maintenance operation supported through ARRA. The errors have been divided into three kinds:
    a. Component identification
    b. Component moving direction (for both translations and rotations)
    c. Components coupling

2) Quantification of the spatial referencing errors occurring when performing the same maintenance operation as Step supported through "video-call support".
3) Comparison between 1 and 2.

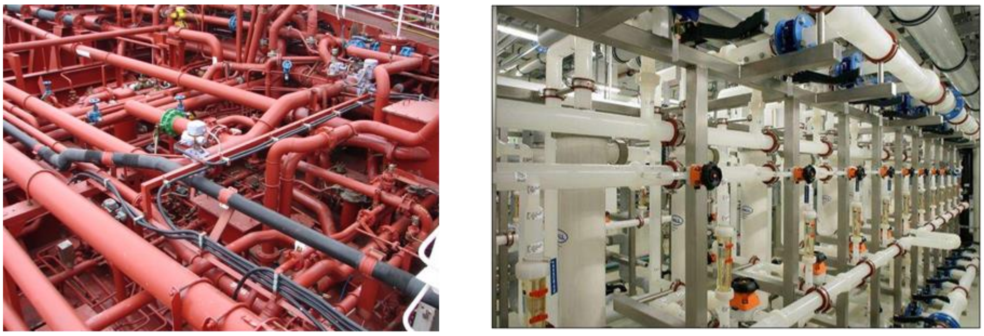
The case study and therefore the maintenance operations utilised for testing purposes are reported in Sect. 4.1. The validation steps 1 and 2 have been calculated utilising the test described in the following Sect. 4.2. The results have then been compared (step 3) and are shown in Sect. 5.

4.1 Validation Case Study

This section describes the case study utilised for validation purposes. The quantitative validation process is then described in detail in sec 4.2. The authors decided to utilise, as a case study, an operation that presents symmetries and difficulties in spatial referencing due to the resemblance of its component. Moreover, the case study had to comply with the following requirements:

1) Hard-copy manuals availability
2) Sufficient task complexity
3) Suitable dimensions for the available lab
4) Low occurrence maintenance hence suitable for the application of AR [11]
5) 3D printed simplified mock-up manufacturability

Therefore, it has been chosen to utilise complex hydraulic/pneumatic piping systems. These kinds of assemblies are common in the oil & gas industry, pharmaceutical plants, energy factories but not only.



(a) (b)

Fig. 6. Examples of piping systems in the industry

Fig. 6 shows two examples of piping systems in the industry. On the left (a), the piping system of a chemical tanker [24], on the right (b) a UPW Installation using PVDF Piping [25]. For performing ARRA's validation test and quantify the improvements in terms of spatial referencing, the mockup shown in Figure 7 was 3D printed and assembled.

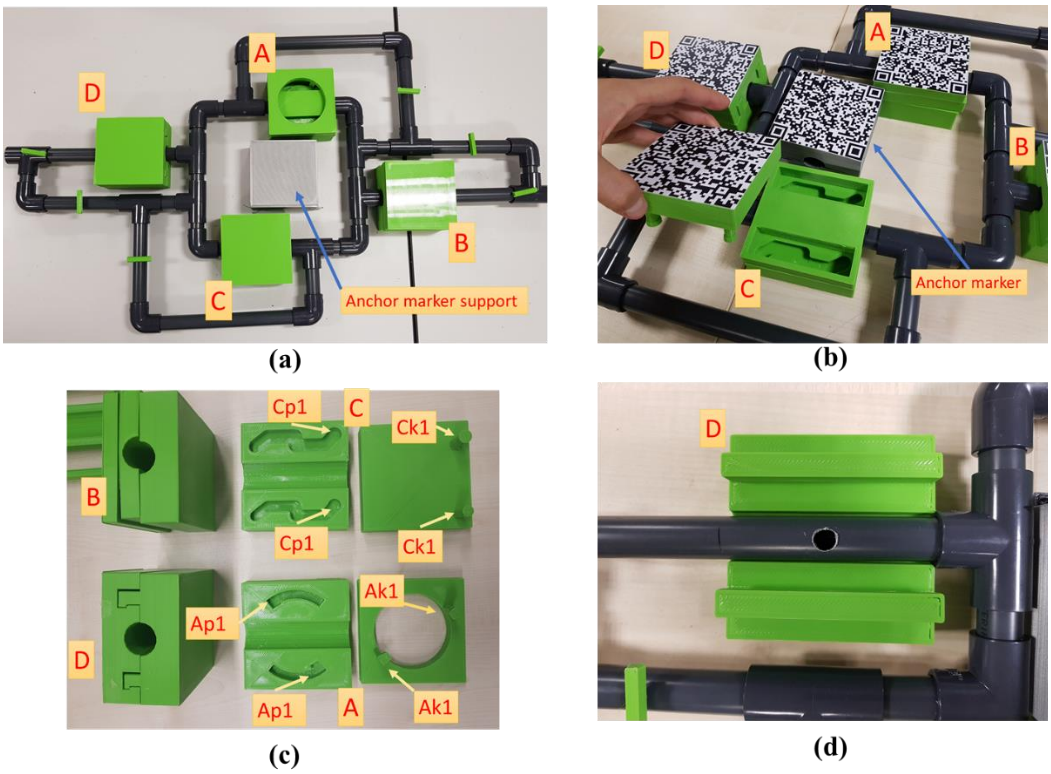


Fig. 7. 3D printed mock-up of piping system for validation purposes

Starting from Fig.7a, the mock-up consists of a piping system built utilizing ½" PVC pipes connected through 90 degrees elbows and tees. The piping path has been designed to have symmetries with respect to the two main piping directions. This has been done to add complications in terms of spatial referencing. Five "boxes" are visible in the figure. The four green ones will be called "locks" from now on. Each lock has a bottom component and a top component. These have been 3D printed and simulate any component which needs to be disassembled in order to be dismounted from its respective pipe. Each one of the four locks (A, B, C, and D) has a different locking system for coupling the top component with the bottom one. The grey box in the middle is the anchor marker support. In Fig. 7b, the markers for allowing object recognition has been applied. Moreover, lock C is opened (top and bottom component are separated) and it is possible to see its internal path. The latter is better shown in Fig. 7c. Locks C and A are opened and laid on the table (on the right). Locks B and D are closed and vertically shown on the left. Similarly, to the shaft-hole coupling, in this mock-up, the authors have designed the locks to have keys (indicated as Ck1 and Ck2 for lock C, as Ak1 and Ak2 for lock A) and paths/holes (indicated as Cp1 and Cp2 for lock C, as Ap1 and Ap2 for lock A). There is only one possible way to assemble the two components of each lock. For instance, Ck1 diameter can only get into Cp1. Finally, in Fig. 7d showed an example of a defect that has to be fixed and lies under lock D. The locks have been designed in CATIA V5 and 3D printed in PLA utilising the Ultimaker 2 printer. A material depositing head of 0.8mm and layers of 0.6mm is utilised.

4.2 Quantitative Validation Test Methodology

This section describes the method utilised for quantifying the spatial referencing error reduction due to the utilisation of ARRA in comparison with video-call support.

Firstly, the quantification of the spatial referencing errors has been carried out separately for ARRA and video-call support utilising respectively the method schematically described in Fig. 8 and Fig. 9. Then the results were statistically analysed and compared for calculating the spatial referencing reduction. Following the timeline, on the top left, the participant is asked to read and sign the consent form as well as providing demographical data. The latter is used only for a qualitative analysis of the sample and does not affect the test results. The participant was then identified as a "novice" and was positioned in front of the assembly to be maintained (as in Fig. 4a) and introduced to ARRA by the observer. He could then request for assistance through ARRA, receive the procedure remotely built by an expert, and carry out the maintenance operation. The possible maintenance operations were eight and consisted of the assembly and disassembly of the four locks.

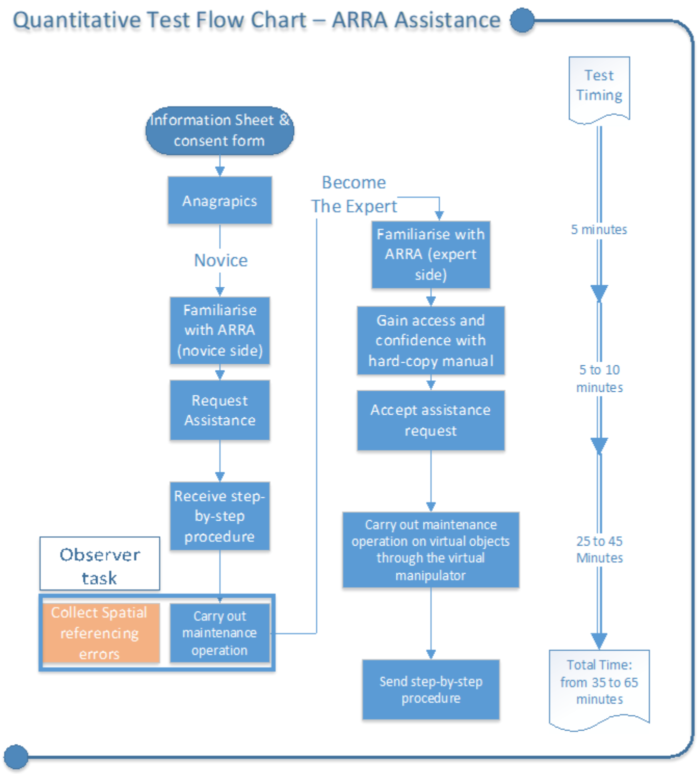


Fig. 8. Schematic representation of spatial referencing errors quantification test for ARRA

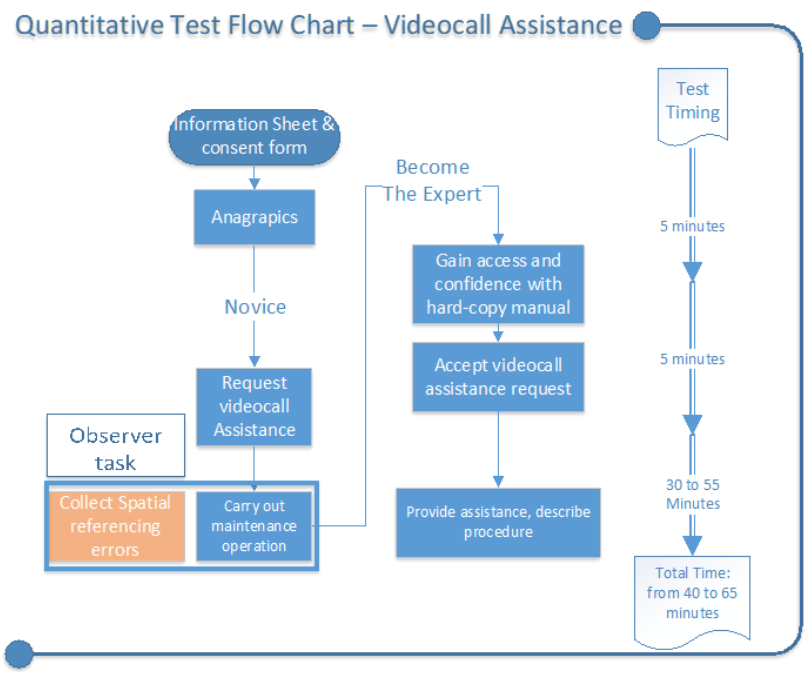


Fig. 9. Schematic representation of spatial referencing errors quantification test for video-call

During maintenance operations, the observer will collect the spatial referencing information. The spatial referencing errors collected in this test can be of three kinds:

1) Wrong object identification
2) Wrong object direction
3) Wrong lock coupling (only applies assembly operations)

The first one occurred when the participant, after receiving the procedure, puts his hands on the wrong lock. The second one occurred when the component of the lock was moved towards an incorrect direction or rotated in the opposite sense. The last one consisted of associating the chosen top component of a lock with the bottom component of a different lock (only applies to assembly operations). The observer collected the data by filling a specifically designed form with a fixed multiple choice. For each of the spatial errors mentioned above, the observer can also choose among two descriptors: "opposite" and "other". The "opposite" was utilised when the participant:

1) Identifies the opposite component (with respect to the axis of symmetry), or
2) Moves the object in the opposite direction
3) Couples the top component with the bottom component of the opposite lock

The "other" was utilised when the participant made a different kind of spatial referencing error. The "correct" was used when no spatial referencing error was made by the participant. The test was completed once the maintenance operation was carried out. The novice participant can now become a remote expert and provide assistance to the next novice participant. Taking advantage of the knowledge the first novice acquired during his test, providing him with more information about the assembly though a hardcopy manual, and showing him how the remote expert interface of ARRA works he is now able to virtually manipulate the locks as a remote expert. The spatial errors collected were compared with the one occurring when the same maintenance procedures were performed through video-call support. In this case, a new participant was placed in front of the assembly and was provided with an RGB camera for video-calling support. The orientation of the camera and the position of the participant with respect to the assembly were random. The randomness was eased by the utilisation of a round table as a working area. On the other side, the expert was a participant that has already done the test as a novice who, moreover, was provided with the hardcopy manual. The observer collects the same data collected for quantifying the spatial errors considering ARRA support. The data collected in both scenarios were compared to calculate the final spatial errors reduction due to the utilisation of ARRA vs. video-call support. Table 1 is provided as an extract of the complete table of data collected during the tests.

Table 1. Extract of the complete dataset table utilised for further analysis

Participant ID	Remote Assistance	Operation ID	Spatial Reference	Error Kind
1	ARRA	4	Correct	Identification
1	ARRA	4	Opposite	Direction
32	VIDEOCALL	3	Other	Coupling
32	VIDEOCALL	5	Correct	Coupling
34	VIDEOCALL	7	Other	Coupling
3	ARRA	1	Correct	Identification
4	ARRA	8	Correct	Direction
45	VIDEOCALL	1	Opposite	Identification
15	ARRA	6	Correct	Coupling

In agreement with the methodology described in this section, Table 1 presents five columns. The first one lists the participant ID. The second column lists the method utilised for RA. The third column represents the operation carried out by the participant. These have been divided in 1-4 for disassembly and 5-8 for assembly of the four locks. The "spatial reference" and "error kind" columns report the data collected by the observer. For instance, in the first row, participant "1" correctly identified the object to be maintained in performing operation "4". The same participant has then wrongly moved the object in the opposite direction as reported in the second row. Participant "1" has been supported remotely through ARRA. The analysis of the data and the results are reported in Sect. 5. The test aimed to quantify the improvement in terms of spatial referencing when performing a maintenance operation remotely supported by ARRA vs. video-call. A total of 60 participants (42 male /18 female) took part in this study. These included students and research staff from Cranfield University with higher education and/or engineering backgrounds as well as not academic people with no engineering background in a 50/50 ratio. Half of them performed the maintenance operation supported by ARRA; the other half were supported by videocall. The average age was 27.9 (M=21, 33, SD=3.48). Half of them performed the maintenance operation supported by ARRA; the other half were supported by video-call. On average, each participant carried out 3 of the 8 operations/tasks available. Each participant test took from 30 to 60 minutes for completion and all the data collected has been stored in compliance with Cranfield University research ethics policy.

5 Analysis and Results

The data has been collected utilising the methodology described in Sect. 4.2, and transcribed in a dataset shown in Table 1. The full table comprises of 450 rows. This number can be also calculated as reported in Equation (1); where *N* is the number of rows, *P* is the number of participants, *O* is the operation performed by the participant, and *E* is the average number of error kinds.

$$N = P \text{ x } O \text{ x } E \quad (1)$$

From the equation above, the number of participants is 60, the operations performed by each participant for testing purposes were 3 and the average number of error kinds was 2.5. The latter was because, as already explained, for disassembly operations 1-4, the error kinds were 2: identification and direction. For assembly operations 5-8, the error kinds were 3: identification, direction, and coupling. Therefore, considering that each operation has been tested the same amount of time, the average is (2+3)/2 = 5.

To examine if a significant association exists between the RA methods utilised (ARRA vs. video-call) in terms of the amount of spatial referencing errors, it is required to perform a statistical test. Due to the nature of the sample, the authors decided to perform Pearson's chi-squared test. The sample is in fact, complies with the two test required assumptions:

1) The two variables should be measured at an ordinal or nominal level
2) The two variables should consist of two or more categorical, independent groups.

The first assumption is verified since ARRA and video-call variables are measured at a nominal level through three categories that do not have an intrinsic order: correct, opposite, and other. The second assumption is verified since the two variables ARRA and video-call are two independent groups since the utilisation of one excludes the utilisation of the other. The result of Pearson's chi-square test is that there is a statistically significant association between ARRA and video-call, $\chi 2(2) = 72.68$, $p < 0.05$. The overall significant effect of the utilisation of ARRA considering all the operations is shown in Fig. 10.

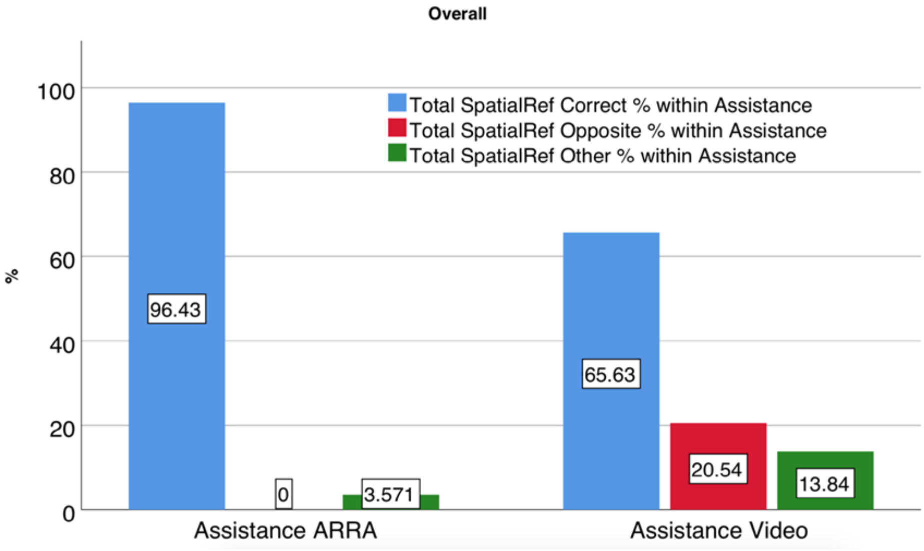
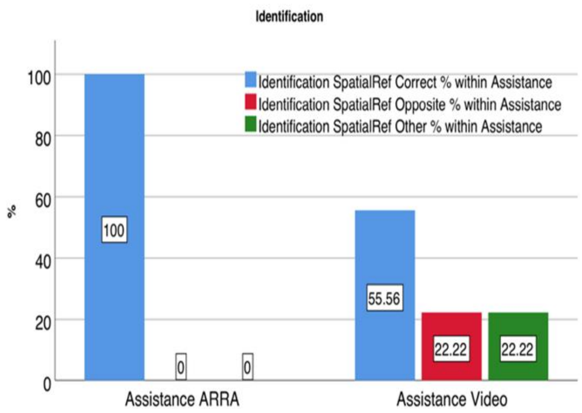
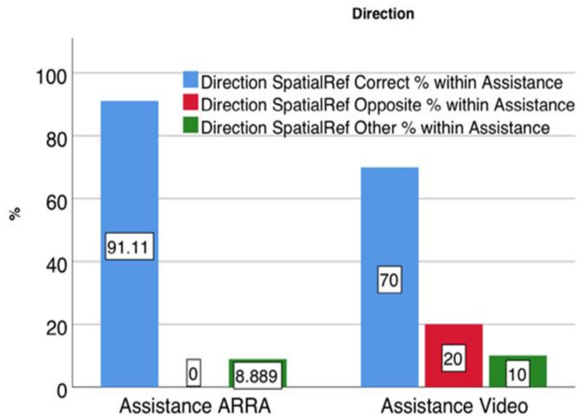


Fig. 10. Overall percentages of spatial referencing errors

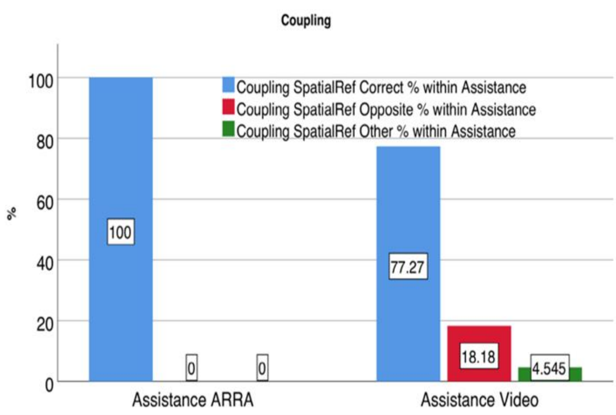
Figure 10 shows that, when utilising ARRA, 96.43% of the tests resulted in "correct" spatial referencing. Only a small percentage of them resulted in other spatial referencing errors. On the other side, about 66% of the tests supported by video-call were performed correctly. About 20.5% of the tests resulted in presenting the spatial error defined as "opposite".



(a)

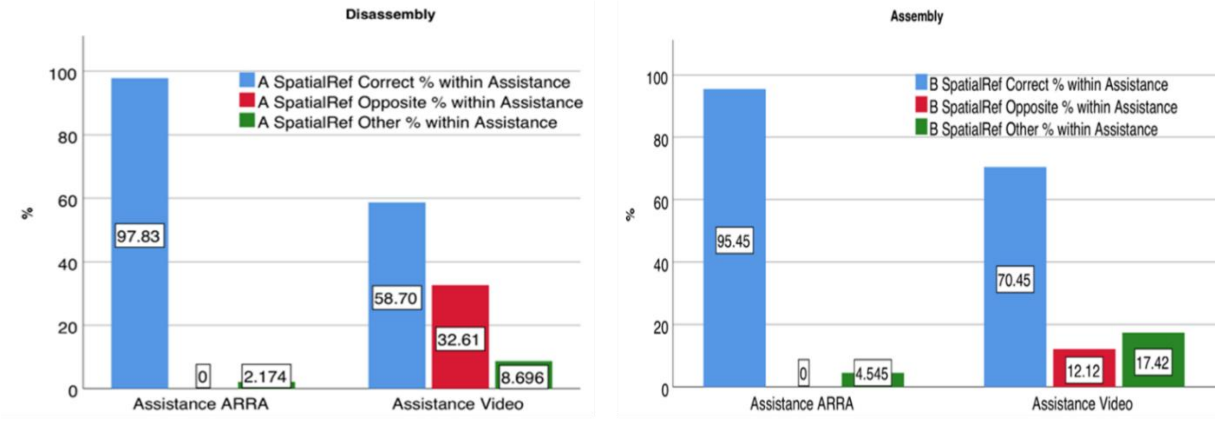


(b)



(c)

Fig. 11. Spatial referencing errors by kind: (a) identification, (b) directional, and (c) coupling



(a) **(b)**

Fig. 12. Spatial referencing errors collected for disassembly and assembly operations

It occurred when the participant:

1) identified the lock located in the opposite position with respect to the assembly symmetry,
2) moved the component in the opposite direction to the one he was expected to,
3) intended to couple the top component of a lock with the opposite bottom of another lock.

Moreover, about 14% of the tests resulted in other kinds of spatial referencing errors. Overall ARRA results in a 30% (correct-correct) improvement in terms of spatial referencing compared to video-call. For further understanding of the correlation between the errors and the operations, it has been found useful to plot the bar-chart of each "error kind" separately. These are shown in Fig. 11. It is worth to notice that ARRA performed perfectly (100% correct spatial referencing) for the identification of the objects (a) and the coupling (c) between the top and bottom components of the locks. About 9% of spatial errors were made in terms of moving directions (b). Furthermore, the authors investigated if the kind of operation (assembly or disassembly) affected the spatial referencing results (Fig. 12). Even though there is not a huge difference for ARRA in supporting an assembly or a disassembly operation, we can notice that video-call support results in slightly different outcomes. More specifically, for the disassembly operations, video-call support resulted in more "opposite" spatial errors than "other" (33% vs 8.7%). For assembly operations the percentages are inverted: 12% "opposite" vs 17% "other". Finally, each of the 8 operations has been plotted separately. Figure 13 reports the 4 disassembly operations.

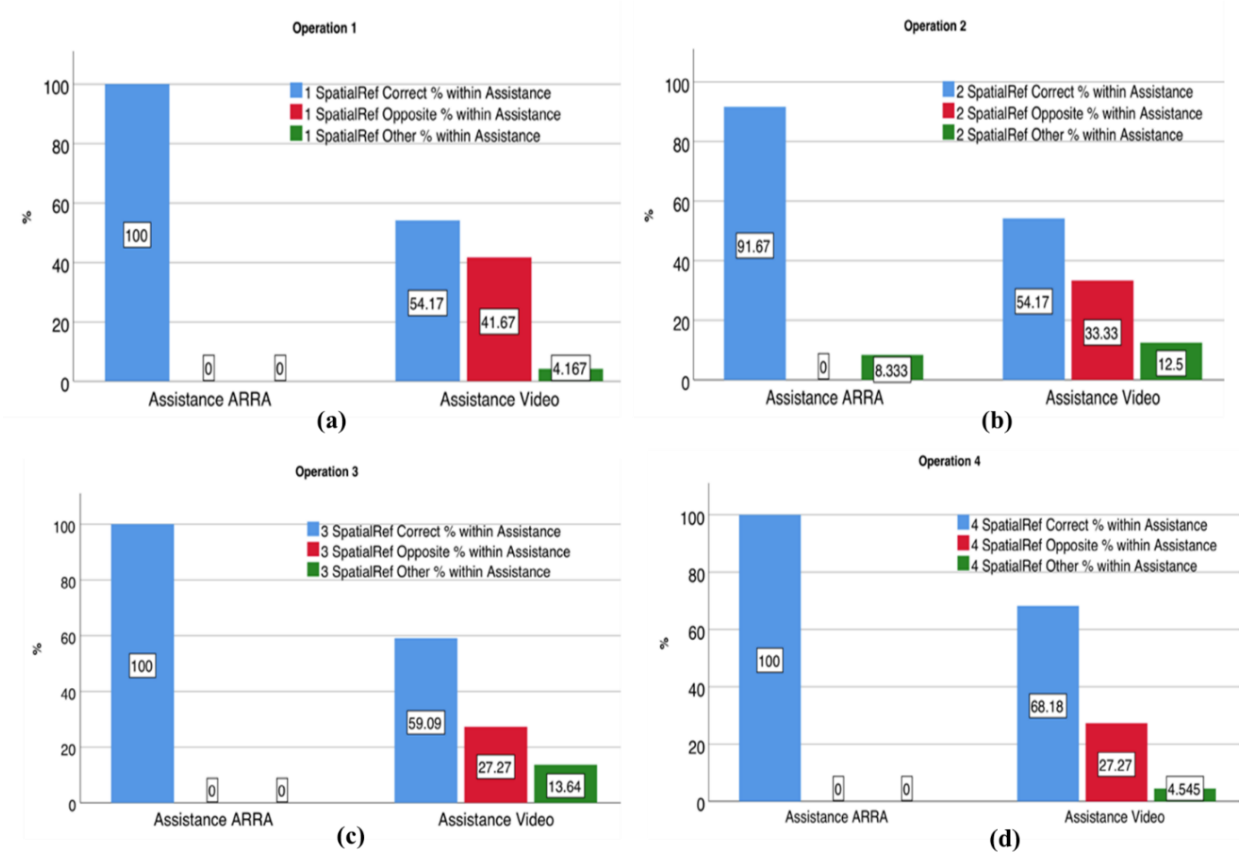


Fig. 13. Spatial referencing errors collected for each disassembly operation separately

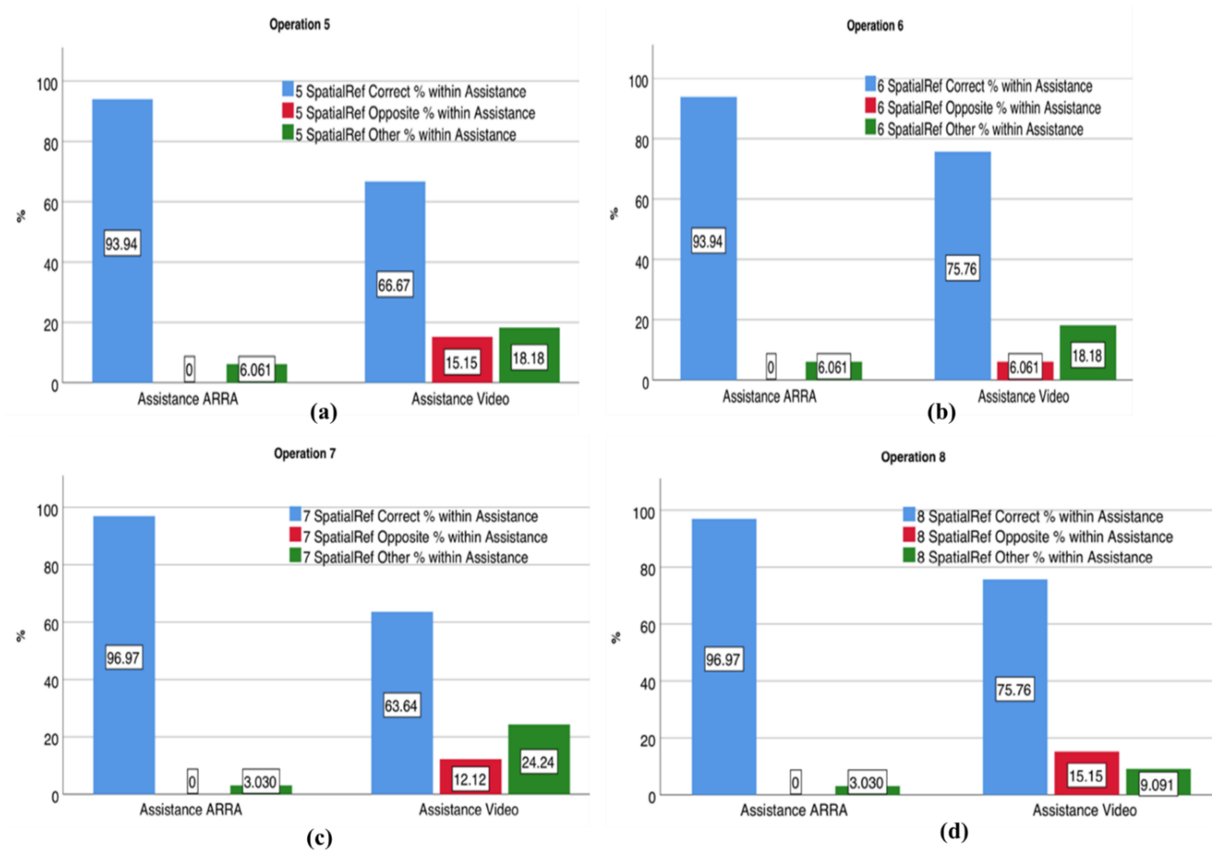


Fig. 14. *Spatial referencing errors collected for each assembly operation separately*

In Fig. 13, the test, which utilised ARRA for disassembly operations (1-4) resulted in near-zero spatial errors. Only operation 2 (b) presents "other" spatial errors. Figure 14 reports the 4 assembly operations, each with the associated percentage of errors. As already shown also by Fig. 12, ARRA performed worst for assembly operations never reached the 100% correct spatial referencing

6 Discussion

This section reports the discussion about the study methodology and results. The authors' intent in developing ARRA was to provide augmented reality support for RA. Moreover, the study focuses on quantifying the improvement in terms of spatial referencing due to the utilization of ARRA vs video-call support for maintenance. ARRA is based on two assumptions:

1) The system is able to recognise and track the object in the FOV of the remote novice maintainer.
2) The CAD models of the objects to be maintained are available.

The participants have been remotely assisted through ARRA or video-call support. Quantitative spatial referencing errors data has been collected. The results have shown a 30% of improvement in terms of spatial referencing when utilising ARRA as remote assistance support vs video-call support. These improvements have been found to be due to an increase of spatial awareness. The AR system efficiency, in fact, is invariant with respect to the technician Point Of View (POV) since it relies only on the real environment configuration. The video-call support, on the other side, relies on the ability of the technicians to communicate and to understand each other's POV.

The authors consider these assumptions plausible due to the recent improvements in image processing, object tracking and recognition, and hardware (processors and sensors) [11, 23]. ARRA has been described in Sect. 3 through a practical example and technical development. Even though in this study the authors utilised some specific hardware and software solutions, ARRA can be developed and implemented differently. Considering the fast advancement of the technology related to AR it could be useful to exploit the utilisation of depth sensors for the recognition of the objects. Moreover, an HMD would be more suitable for industrial applications. It could not be utilised in this study only for validation reasons. The observer of the empirical tests that have been carried out needed to clearly understand the evolvement of each test for collect the data required for assessing the spatial referencing improvements.
This study focuses on quantifying the spatial referencing errors occurring when utilising ARRA vs. video-call support for RA. The methodology utilised for the empirical tests took inspiration from similar studies [26][27][28]. The case study utilised, even though apparently might not seem complex, hides several challenges. First of all, the full assembly presents symmetries and similitudes. All the components have the same external shape and color and, therefore, are difficult to be identified through voice indications or hard-copy manuals. Moreover, every one of the 4 locks has a different unlocking system. All together comprise x, y, and z translations and z rotation. The tests were planned carefully and the small space was given to subjectivity. The observer was provided with multiple-choice forms and a detailed schematic process for carrying on the tests. Regarding the results, ARRA performed always better than video-call support in terms of spatial referencing. This is because AR relies on the spatial references recognised by the software and is invariant with the orientation of the camera. Video-call

support, on the other side, relies on the voice communication between the expert and the novice. The reference system, which is in the expert mind might be different from the one of the novice. For instance, if the expert indicated to grab "the object on the right", the novice might have grabbed the object, which was at his right. Sometimes this resulted in grabbing the correct object, but sometimes not. This is the reason why, for all the operations (see Fig. 13 and Fig. 14), video-call support always presented an unneglectable percentage of spatial referencing errors of the kind "opposite". Furthermore, from the types of errors: identification, direction, and coupling (Fig. 11), we can see that ARRA only resulted in spatial errors within the direction category. It means that, when ARRA support indicated a direction of movement for any object in any operation, it resulted in a 10% error of the kind "other". In other words, the participant did not move the object towards the correct direction and not even the opposite direction. He moved the object towards a completely different direction. The authors found a plausible justification thanks to Fig. 13b. The latter shows that within the 4 disassembly operations, only operation "2" presented directional spatial errors when utilising ARRA. Operation "2" consisted of the disassembly of the top component of lock B (see Fig. 7a). It was done by rotating the top component around the "z" axis and was also reported in the practical example in Fig 4. Due to the inclination of the camera with respect to the assembly, the rotation was sometimes (10% of the time) confused with a pulling movement and therefore resulted in a spatial referencing error.

7 Conclusion and Future Work

This study proposes Augmented Reality support for Remote Assistance: ARRA. ARRA allows a remote expert to visualise in real-time the novices' maintenance problem and guide him through the solution. The remote expert can build step by step procedures through the virtual manipulation of the virtual objects and overlay the procedures into the real novice's working environment. Among the challenges in remote assistance, ARRA attempts to overcome the spatial referencing issues. These can be seen as the difficulties the remote expert has in explaining the novice what he has to do without knowing his spatial references and having full control of the maintenance environment. Therefore, ARRA has been tested and validated considering three spatial referencing errors: 1) the identification of the objects, 2) the movements of the objects, and 3) the coupling of two objects. The case study utilised was a mock-up of a piping system. The comparison of ARRA was made with remote assistance through video-call. The results indicated an overall improvement of 27% in terms of correct spatial referencing operation when utilising ARRA in comparison with the video-call. Moreover, ARRA performed perfectly when considering identification and coupling errors. The tests regarding the direction of the objects, on the other side, showed an unneglectable percentage of errors of about 10%. Further research needs to investigate if the utilisation of HMD and a more advanced UI in ARRA could overcome directional spatial referencing errors and close to 100% of correct operations for similar assemblies.

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BIOGRAPHIES

Riccardo Palmarini completed his PhD from Cranfield University in 2019 and currently works as an Instrument and Automotion Engineer at TechnipFMC. Riccardo also completed an MSc at Cranfield University in Aircraft Vehicle Design. His PhD project focused on developing Augmented Reality (AR) based visualisation system to support with the delivery of maintenance and\or manufacturing.

Iñigo Fernández del Amo completed his PhD at Cranfield University in 2020 in Augmented Reality for Maintenance. His primary interest is in how Augmented Reality systems can capture knowledge from maintainers to provide sustainable efficiency improvements. Iñigo graduated last year from a double-degree in Industrial Engineer and Manufacturing Consultancy between the Polytechnic University of Madrid (UPM) and Cranfield University. He has won the Cranfield Vice-Chancellor's Prize 2017 for the most outstanding MSc student.

Dedy Ariansyah completed his PhD from Politecnico di Milano in 2018 in methods and tools for product design and held a post-doctoral position in Augmented Reality (AR) and Virtual Reality (VR) development for manufacturing and maintenance until 2019. He currently holds a research fellow position at Cranfield University since 2019 in AR for Through-life Engineering. His current research is funded by EPSRC under Digital Toolkit for optimization of operators and technology in manufacturing partnerships (DigiTOP) project. His work is focused on the integration of Digital Twin and AR, including the Human Factors aspect.

John Ahmet Erkoyuncu completed his PhD from Cranfield University in 2011 in uncertainty modelling for maintenance and completed and MSci degree in Applied Statistics from Imperial College London. Since 2020, John is a Professor of Digital Engineering in Digital Service Engineering at Cranfield University. John is active with Innovate UK and EPSRC funded projects in the UK around research topics: digital twins, augmented reality, digitisation (of degradation assessment), and simulation of complex manufacturing and maintenance procedures. Prof. Erkoyuncu has published over 100 conference and journal papers in internationally leading venues. John is a Chartered Engineer and a Member of IET.

Professor Rajkumar Roy is the Dean of School of Mathematics, Computer Science and Engineering at City, University of London. He joined City, University London from Cranfield University, where he was Director of Manufacturing. Professor Roy holds a PhD in Computing from the University of Plymouth (UK) and BEng and MEng degrees in Production Engineering from Jadavpur University in India. He started his career as an engineer at Tata Motors; pioneered research in Through-life Engineering Services (TES) with Rolls-Royce, BAE Systems, Bombardier Transportation, the Ministry of Defence and Babcock International; and established an internationally known TES Centre. Professor Roy's cost engineering and obsolescence research has transformed contemporary understanding of the engineering effort required to design, make and support high-value products, resulting in tools used by BAE Systems, Airbus, the Ministry of Defence, Rolls-Royce, and Ford Motor Company. Professor Roy is a Founding Editor-in-Chief of the Elsevier Applied Soft Computing journal and a Fellow of the CIRP (International Academy for Production Engineers), the Institution of Engineering and Technology (IET), the Institute of Engineering Designers (IED), and the Higher Education Academy (HEA).