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RESEARCH ARTICLE

Fast Augmented Reality Authoring: Fast Creation of AR Step-by-Step Procedures for Maintenance Operations

RICCARDO PALMARINI[1], IÑIGO FERNÁNDEZ DEL AMO[1], DEDY ARIANSYAH[1], SAMIR KHAN[1], (Member, IEEE), JOHN AHMET ERKOYUNCU[1], AND RAJKUMAR ROY[2]
[1]Cranfield Manufacturing, School of Aerospace, Transport and Manufacturing, Cranfield University, MK43 0AL Cranfield, U.K.
[2]School of Mathematics, Computer Science and Engineering, City, University of London, EC1V 0HB London, U.K.

Corresponding author: John Ahmet Erkoyuncu (j.a.erkoyuncu@cranfield.ac.uk)

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ABSTRACT Augmented Reality (AR) has shown great potential for improving human performance in Maintenance, Repair, and Overhaul (MRO) operations. Whilst most studies are currently being carried out at an academic level, the research is still in its infancy due to limitations in three main aspects: limited hardware capabilities, the robustness of object recognition, and content-related issues. This article focuses on the last point, by proposing a new geometry-based method for creating a step-by-step AR procedure for maintenance activities. The Fast Augmented Reality Authoring (FARA) method assumes that AR can recognise and track all the objects in a maintenance environment when CAD models are available, to knowledge transfer to a non-expert maintainer. The novelty here lies in the fact that FARA is a human-centric method for authoring animation-based procedures with minimal programming skills and the manual effort required. FARA has been demonstrated, as a software unit, in an AR system composed of commercially available solutions and tested with over 30 participants. The results show an average time saving of 34.7% (min 24.7%; max 55.3%) and an error reduction of 68.6% when compared to the utilisation of traditional hard-copy manuals. Comparisons are also drawn from performances of similar AR applications to illustrate the benefits of procedures created utilising FARA.

INDEX TERMS Augmented reality, authoring, content, digital engineering, maintenance.

I. INTRODUCTION

AUGMENTED Reality (AR) is an innovative technology that aims to enhance the human perception of reality by providing digitally created content in the real context [1]. Another definition has been provided by Azuma [2] who stated that an AR system should have three characteristics: Combine real and virtual, 2) Interactive real-time, and 3) Registered in 3-D. AR applications have been developed and tested in a wide range of fields: medical applications, marketing, entertainment, education, maintenance, and manufacturing [3], [4]. This article focuses on Maintenance, Repair, and overhaul (MRO) operations. MRO operations impact the lifecycle cost of industrial equipment [5]. The increasing complexity and automation of industrial machinery require new technologies for ensuring reliability and productivity through MRO operations. In the aviation field, MRO operations costs can reach 80% of the entire aircraft lifecycle [6]. MRO operations strongly rely on maintenance technicians' expertise [7]. The latter can affect both the errors and completion time involved

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in the MRO operation thus influencing the MRO cost. AR can help reduce errors and completion time by allowing easy access to MRO information which today belongs mostly to the expert maintainers' memory [8]. Even though the advantages (time savings and error reductions) of AR in maintenance have been proven by academics, the technology still lacks the robustness and flexibility to become of common use. Among the main research topics, it is possible to find [9], [10], [11]:

- Tracking and recognition of performances
- Hardware (head-mounted displays) capabilities
- Contents-related issues

The last one comprises difficulties in creating and managing content for AR applications. The traditional process of creating content (a.k.a. authoring) for AR requires different professionals: programmer, animator, CAD modeller, and AR developer. More innovative authoring solutions which provide a friendly user interface and content adaptation have also been proposed ([12], [13], [14]). However, they still require a lot of human effort and have limited flexibility. This article contributes to this gap by implementing an AR within a maintenance application. For authoring "AR step-by-step" procedures to guide a non-expert technician in carrying out a maintenance task "Step-by-step AR instructions" or "procedures" is a common terminology which refers to the action of gradually providing a set of information at each step of an MRO operation. The data considered in this project is visual (3D animations). The method developed and validated has been named FARA: Fast Augmented Reality Authoring. **The novelty of this work lies in the approach that FARA is a humancentric method for authoring animation-based procedures with minimal programming skills and manual effort required when learning to use the software features for creating step-by-step AR instructions**. It takes inspiration from Fast Programming Robots that enable users to teach robots by demonstration. Similarly, FARA allows users to teach an AR system how to overlay the virtual content into a real environment without programming.

This article is structured as follows. The research background and motivation are provided in Sections I and II. This is followed by a description of FARA: how it works and its structure and the detailed methodology for FARA's validation. This includes the quantitative test design (Section IV-A), the case study utilised (Section IV-B), and FARA's implementation in an AR system for testing purposes (Section IV-C). Analysis and results are reported in Section IV-C. Finally, the discussion of the results and the conclusions are presented in Sections V and VI.

II. RESEARCH BACKGROUND AND MOTIVATION

This research focuses on the creation of content for AR (authoring) for maintenance applications which are known as one of the main problems that prevent AR to become mainstream. The simple and easy creation of AR content is not currently available. The authoring process is time-consuming and expensive [15]. The contents are now implemented in AR as "standalone" programs by programmers [16]. Comprehensive reviews of AR authoring for maintenance applications have been done [10]. The remaining paragraphs highlight some of the existing efforts for content creation and identify the crucial gap of AR authoring for industrial implementation to be addressed in this work. **The main knowledge gap is that current authoring environments require comprehensive programming and graphical expertise**. The most common tools for authoring AR content comprise plugins, software development kits (SDK), and graphical programming languages. Among these, it is worth mentioning Unity, Unreal, Panda3D, ArToolkit, Vuforia, and Max/MPS.

Nowadays, only a few have attempted to ease and de-skill the authoring process. Shim et al proposed an interactive features-based AR authoring tool [17]. This allows users to rotate, move, enlarge merge and occlude virtual objects the virtual objects visualized over a 2D printed marker. The mentioned transformations are done through marker interaction and gesture interaction. Similarly, Yang et al proposed an authoring tool that takes advantage of a mobile device to interact with the virtual objects visualized through an HMD [18]. Both approaches do not require any programming skills and are not time-consuming for the content creator. Still, the solution does not allow the creation of animation, which is powerful in the maintenance environment [6], [19].[1] Csurka et al proposed SUGAR, as an easy-to-use AR editor that does not require programming skills [20]. However, part of the creation of the content must be done through the SUGAR editor. The latter requires the content creator to input the picture of the working environments and manually create or import the virtual objects and animation that users want to over-impose on the real environment at each step of the maintenance procedure. Even though the advantages compared with the traditional authoring methods have been proven, it is the authors' opinion that most methods are still time-consuming. Zhu et al proposed an on-site authoring tool that allows maintenance technicians to change or create information instances related to maintenance procedures [21]. This means that only text information can be created and edited. Other authoring solutions have been used or proposed in the literature [22], [23], [24], [25], [26], [27]. Using these authoring solutions requires some knowledge and a manual process in understanding how to use the software features such as creating and positioning the 3D animation on top of the real component.

Taking advantage of the valuable contributions of previous studies, the aim of simplifying the authoring process of AR procedures should remain and will likely help to implement AR in the industry. The availability of AR authoring tools that can be operated by non-programmers and non-AR experts is essential for the success of AR technology in both the maintenance field and other areas [15]. The approach proposed

[1]It must be noted that step-by-step animations might not always be required.

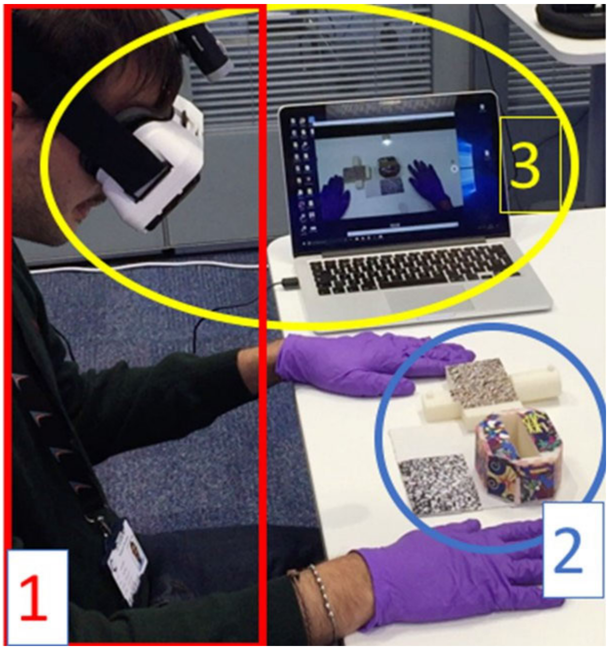

FIGURE 1. Maintenance environment simulation for testing purposes. The environment includes the technician (Nr 1), the product to be maintained (Nr 2) and FARAIS (Nr 3).

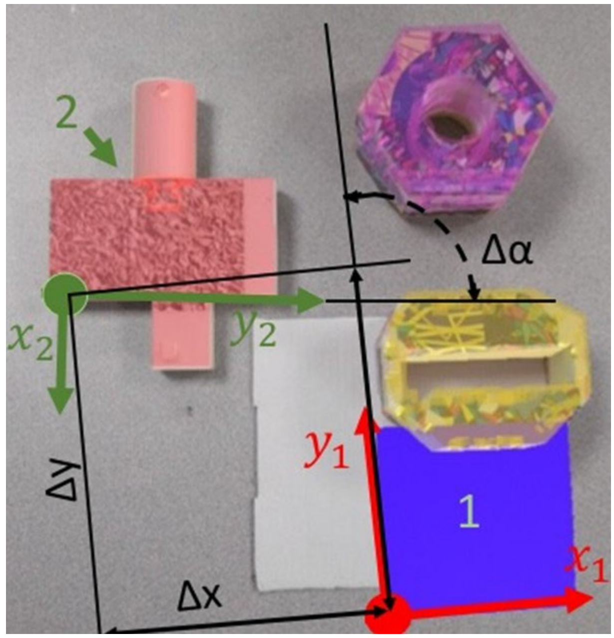

FIGURE 2. 2D graphical representation of "transform". The transformed vector of object 2 is (Δx, Δy, $\Delta \alpha$).

in this article is an authoring technique that automates the creation and positioning of 3D animation content overlaid on the physical components.

III. FAST AUGMENTED REALITY AUTHORING

Fast Augmented Reality Authoring (FARA) aims to overcome the contents-related issues previously described and therefore ease the implementation of AR in the industry. Its name implies "fast programming" when implemented in an existing AR system for maintenance. In this context, "fast programming" indicates "fast AR contents-creation for maintenance procedures". From now on, the authors will refer to any AR system for maintenance implemented with FARA as FARAIS: FARA Implemented System. FARAIS is a tool for easy knowledge transfer from experts to non-expert technicians within procedural operations (e.g., dis/assembly, repair, inspections). It will allow the expert (user confident with the maintenance procedures) to "record" the MROs and the non-expert to access the MROs in a "step-by-step" format. Ideally, a FARAIS would be suitable for any operation involving humans, e.g., both preventive and corrective maintenance. FARA is based on two assumptions. The first one is that current object recognition and tracking issues [10] will be solved by providing reliable and real-time tools that can identify objects independently from the light condition and background noise. The second hypothesis is that CAD models are available for the components involved in any maintenance procedure.

A. HOW FARAIS WORKS: A PRACTICAL EXAMPLE

The FARAIS shown in this example has been developed using commercial hardware and the open-source limited versions of Vuforia and Unity 3D software. These will be described in Section IV-C. The procedure selected is the assembly of a mock-up designed and utilised for testing purposes. It will be described in Section IV-B. First, consider the maintenance environment shown in Fig 1. It includes the maintainer (Nr.1), the product to be maintained (Nr.2) and FARAIS (Nr.3). There are two scenarios: 1) involving an expert technician, and 2) involving a non-expert technician.

1) SCENARIO 1 – EXPERT TECHNICIAN

In this scenario, FARAIS "captures" the expert technician's knowledge. The expert has to carry out a maintenance procedure that they are confident with, on the product shown in Fig 1 (Nr.2). He accesses FARAIS through the hardware provided. Here, it is a "head-mounted video-see-through display". Before starting the procedure, he will select "record mode" to "capture" the procedure and select a name: e.g., "Procedure 1". Once started the procedure, FARAIS will simultaneously perform three actions:

- Recognise and track the real objects in the Field of View (FOV) of the technician
- Store the transforms of the real objects in the table dedicated to "Procedure 1"
- Overlay the virtual objects over the real ones utilising the "basic overlay rule" available on a database (DB)

The first action comprises tracking the position and orientations of the objects. The second one means that the positions

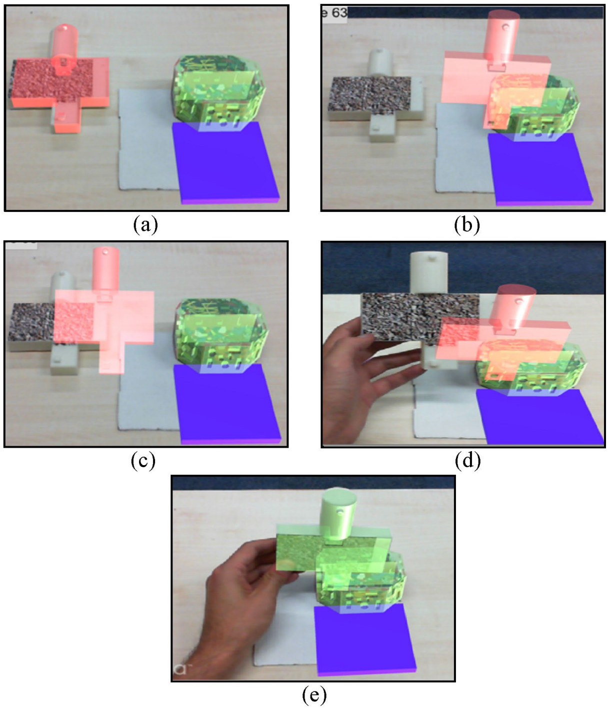

FIGURE 3. AR step-by-step procedure animation example.

and orientations are stored as "transform". A transform is a vector which consists of the linear and angular distances between an object and an anchor object. The third one refers to the capability of an AR system to overlay a virtual object on a real one following a predetermined rule. The basic rules of alignment and scale, as well as the rendering information, are called, in this article, the basic overlay rule. Once the procedure is completed, the expert technician can quit the "record mode" through the UI. FARAIS will automatically build the AR step-by-step "Procedure 1". The "How" is explained in Section IV. The maintainer's effort in creating the AR step-by-step procedure is low as the only duty is to press the record button and perform the maintenance procedure as usual. It is worth mentioning that video recording is performed by FARAIS.

2) SCENARIO 2 – NON-EXPERT TECHNICIAN

In this scenario, FARAIS suggests a "step-by-step" AR procedure to a non-expert technician. The non-expert operator must do a maintenance procedure that he has not done before on the product. He/she accesses FARAIS through the hardware provided. In this case, it is a head-mounted video-see-through display. Before starting the procedure, he will select "play mode" and input the procedure name he wants to perform (e.g., "Procedure 1"). At this point FARAIS will:

- Recognise and track the real objects in the Field-Of-View (FOV) of the technician
- Overlay the virtual objects over the real ones following the basic overlay rule
- Find "Procedure 1" in its DB
- Show the step-by-step AR "Procedure 1"

The latter consists of animating the virtual objects on the real ones suggesting the positions and orientations that the real objects must reach at each step. An example is reported in Fig 3.

First, FARAIS recognises the objects and overlays the corresponding virtual objects utilising the basic overlay rule available on the DB (Fig 3a). Then, the virtual object animates detaching from the real object and moving to the target position and orientation as suggested by the selected procedure (Fig 3b, 3c, and 3d). It is worth noting that FARAIS also takes into account user interaction. For instance, if the technician moved the real object in the opposite direction, the animation would start from the position of the real object and make a new trajectory to get to the final position. It will be done by getting first closer to the recorded trajectory, and then continuing with the recorded animation. When the technician puts the real object in the target position, the virtual object will become green (Fig 3e). FARAIS will then move to the next step of the procedure showing the next animation. The screen shows the message "Procedure Completed" when the procedure is completed.

B. FARA METHOD

FARA is a method that, integrated with an AR system, forms what in this article has been named FARAIS. On one hand, the AR system can recognise the environment by performing object recognition and tracking and overlaying virtual objects on the real environment following pre-programmed rules (e.g., overlying the virtual object over the real one by overlapping the corners). On the other hand, it provides the maintainer with the ability to produce the virtual overlay rule by collecting the data from the MRO. This formalizes the AR step-by-step procedures. The FARA method is schematized in Fig 4. The figure is divided into three main squared areas: FARAIS, AR system, and FARA. This division is meant to show that the union of an AR System and the FARA method becomes FARAIS. In simple words, FARAIS consists of an AR system (hardware and software) which utilises FARA to record and display AR step-by-step procedures. The inputs (arrows in) required by FARA are the AR system outputs (arrows out) reported at the top of Fig 4:

- The object recognition and tracking data
- Virtual object overlay basic rule
- The User Kind (UK)
- The Procedure Number (PN)

The first input consists of the geometrical transforms in space related to the objects in the environment. Usually, an AR system can recognise an object and track it by estimating its pose: the relative position and orientation of an object in space concerning the camera. These can be translated into a transform relative to an anchor object in the scene. The second input consists of the basic information for overlaying the virtual object over the real object. The third input indicates the experience level of the operator utilising the AR system. For this study FARA only considers two levels of users:

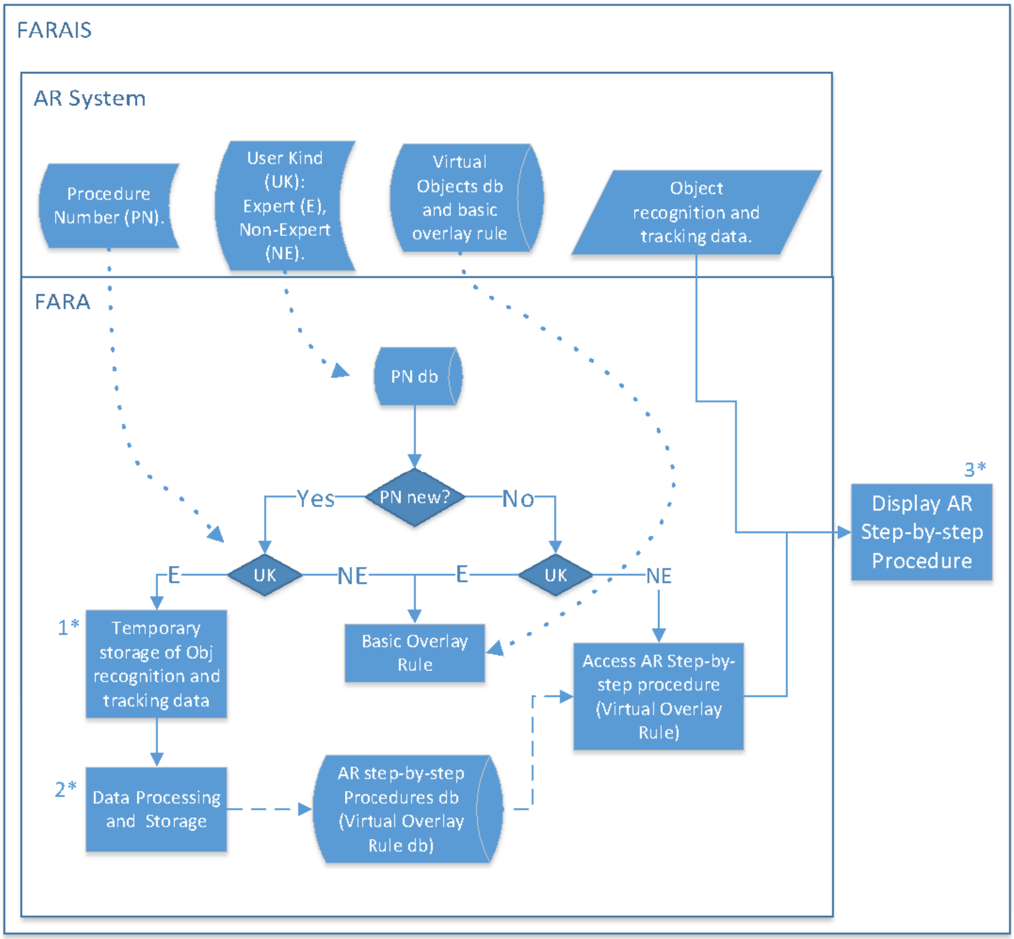

FIGURE 4. **FARA method. The arrows in and out represent the inputs and outputs of each process. The dotted lines refer to the pre-defined input that do not depend on any decisional choices. The firm lines are driven by decisional choices among alternative options.**

Experienced (E) and Non-Experienced (NE). The last one is an "id" used for identifying the maintenance procedure that is going to be carried out by the maintainer. It is relevant to note that potentially, all of them can be identified without input from the operator. Having all these 4 inputs, FARA will first check the procedure "id" and then the user experience level. Only in two cases, FARA will proceed. More specifically, if the procedure "id" is not already available on the DB and the user is experienced, FARA will go through the processes "1*", and "2*" in Fig 4. This is the scenario described in the practical example in Section III-A1. On the other hand, if the procedure is already available on DB and the user is non-expert, FARA will go through the process "3*". This is the scenario described in Section III-A2. In the other two possible combinations, "new procedure/non-expert user" and "available procedure/expert user", FARA will not go through any process. While process 1* is commonly utilised for software development, processes 2*, and 3*, in Fig. 4, have been designed for FARA.

1) PROCESSING DATA

This process modifies the data acquired by the AR system and temporarily stored at process 1* in Fig 4. The "raw" data is acquired in real-time. Whilst progressively filling the rows of a 2D table as time advances, each row needs object recognition and tracking information related to one of the objects in the environment at each time, *ti*. FARA is a geometrical-based method. Hence, the information utilised is (x, y, z) positions and (α, β, γ) rotations. As stated before, these together build the transformed vector $(x, y, z, \alpha, \beta, \gamma)$. An example of the data collected for one object within one MRO is reported in Fig 5a. For simplicity, rotations are not shown. The data acquired is then smoothed (Fig 5b). The data acquisition will have different errors due to the object recognition and tracking system. These have to be deleted or modified to store the correct information. In this example, due to the dimensions (distances and time) of the case, the author used exponential smoothing, applying a threshold of 40mm and 2 seconds. It means that any transformation in

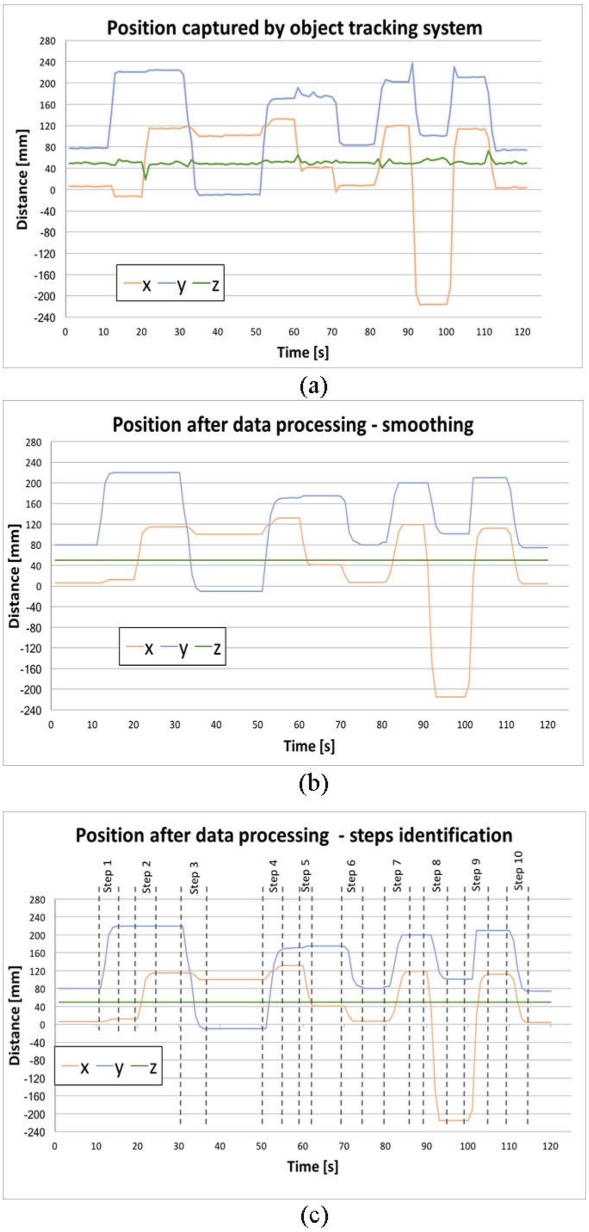

FIGURE 5. Data processing applied by FARA in process 2* shown in Fig 4.

space smaller than 40 mm that lasted for less than 2 seconds has been deleted since it is not considered a movement, but a tracking error. The threshold has been selected arbitrarily based on the author's experience in this case. The process can potentially be automated. Once the table is corrected, process 2 will divide the transforms into groups to identify the procedure steps. For splitting the steps, FARA considers that each step is completed when the transforms of the objects in the environment do not change for a predefined amount of time. In this case, the minimum amount of time considered is 2 seconds. For instance, in Fig 5c, it is possible to see that "Step 3" has been identified between the non-variation of (*x, y, z*) after "Step2" until the re-stabilization of (*x, y, z*) that follows the variation of *y* from 220mm to 10mm. It is worth

TABLE 1. INclination questionnaire.

Question	Score (1-10)
Experience with Digital Engineering	5
Experience with Tablets	8
Experience with AR	1
Experience with Maintenance	6
Experience with Dis/assembly	6
Experience with Puzzles	5

clarifying that these processes are automated by selecting the threshold of time and distance required for both the smoothing and the step identification. The step information is then stored and, together with the tracking data, represents the AR step-by-step procedure.

2) SHOW AR PROCEDURE OVERLAY RULE

This process aims to create and show the step-by-step AR procedure created to the non-expert operator. The process for its creation takes three inputs:

- Live stream of object recognition and tracking data
- Transforms table was corrected and updated with the steps created in the process "2"
- Virtual object basic overlay rule

The first one is provided in the same format as the one stored: transforms of the objects involved in the maintenance procedure. This will be compared every second with the first transform of the AR step-by-step procedure built-in process "2" Fig 4. If they differ, the AR step-by-step overlay rule will be created by gradually positioning the virtual object on the target position. An example of the animation produced is shown in Fig. 3. When the real object transform reaches the correct transform, the correct transform becomes the next row of the table, and another animation will be shown. When all the transforms in the table related to the first step are completed, process "3" will move to the next step until the procedure is completed.

IV. TEST DESIGN AND METHODOLOGY

FARA has been described in Section II. Its advantages in terms of time-saving and low-effort requirements for creating AR step-by-step procedures have been described (Section III-A1). It is essential to validate if FARAIS' step-by-step procedures created with the method described in Section III-B are as valuable as the contents created using traditional methods. If so, it would be clear that FARA could provide a step forward to ease AR implementation in Industry and partially solve content-related issues by providing an intuitive tool for creating AR content. The approach taken by the authors to validate FARA's method consists of two steps:

- Quantification of the average time and errors improvements of a maintenance procedure carried out by using a FARAIS versus the same maintenance procedure carried out by using a hard-copy manual
- Comparison of the results of the quantification with the average time and error improvements of a maintenance procedure carried out using a traditional AR system

versus the same maintenance procedure carried out using a hard-copy manual

While the latter can be found in literature, the first one has been calculated utilising the test described in the following Section IV-A.

A. THE QUANTITATIVE TEST

This section describes the test carried out for quantifying the time/error improvements within a maintenance procedure due to the utilisation of FARAIS versus a hard-copy manual. The quantitative test methodology is described in Fig 7. Starting from the top, the participant is asked to answer a short Likert scale inclination questionnaire in Table 1.

A higher average score for the first three or the last three questions corresponds to a more AR or maintenance-oriented profile. Based on the results, the participant will be assigned to one between the Contents Creator (CC) and Contents Tester (CT) groups. The first is for maintenance-oriented profiles and the second is for AR-oriented ones. In the first case, the CC is then asked to carry out different MRO operations using a hard-copy manual. He is given an initial time to read the manual and become confident with the objects and then start the procedure. The observer will measure the time and errors by filling out a pre-designed form that lists the errors inserted in the mockup. These will provide the ''dataset1'' regarding the hard-copy manual supported maintenance procedure. At this point, the CC will be allowed any amount of time until he becomes an expert in performing the maintenance procedure. No data is collected in this phase. The CC can now utilise FARAIS described in Section III-A1 and create an AR procedure. Each CC had to create four tasks in which each task was taken and mixed up with each task from different CCs. In total, there were four tasks from four different CCs to be used by each CT. If identified as CT, the participant is firstly inducted about the AR application and how it works and then is asked to perform the same MRO operation carried out by CCs. During the latter, the observer will collect the time and error data which will provide the FARA-support maintenance procedure ''dataset2''. In both datasets, the time has been recorded in seconds and the number of errors has been stored. It is worth mentioning that the MRO operations and the product to be maintained have been designed ad-hoc. Explicit errors have been inserted in the mock-up design for ensuring the objectivity of the data collection. ''dataset1'' and ''dataset2'' will then be compared to quantitatively extract eventual improvements in terms of time-saving and number of errors. It has been done through the inferential statistical analysis reported in Section V-A. The quantified results will then be compared with the ones found in the literature related to traditional AR systems for supporting maintenance. Results are reported qualitatively in Section V-B.

B. THE MAINTENANCE CASE STUDY FOR TESTING PURPOSES

In this section, the case study utilised for testing purposes is described. The real case maintenance scenario chosen in this study is the dis/assembly maintenance of a hydraulic valve In the selected case study, the authors designed and 3D-printed a ''maze'' which has similar translations and rotations of its component. The mock-up CAD model is shown in Fig 6c and the 3D printed version is shown in Fig 6d. The assembly consists of three components: the basement, the board, and the top. The basement has a planar maze that has to be completed by sliding (right, left, up, and down) the bottom part of the board. Three errors have been inserted in the planar to ease the collection of the data during the test. Once completed the assembly of the board into the base, the top component will be assembled into the board. It has a cylindrical maze that has to be completed by rotating (CW or ACW) and sliding (up and down) the top component on the top side of the board component. Also in this, the authors inserted three dis/assembly errors for testing purposes. These consist of the misplacement of the assembly components concerning each other in three different phases of the assembly. For easing Vuforia's object recognition, the surfaces of the objects have been enriched with colour.

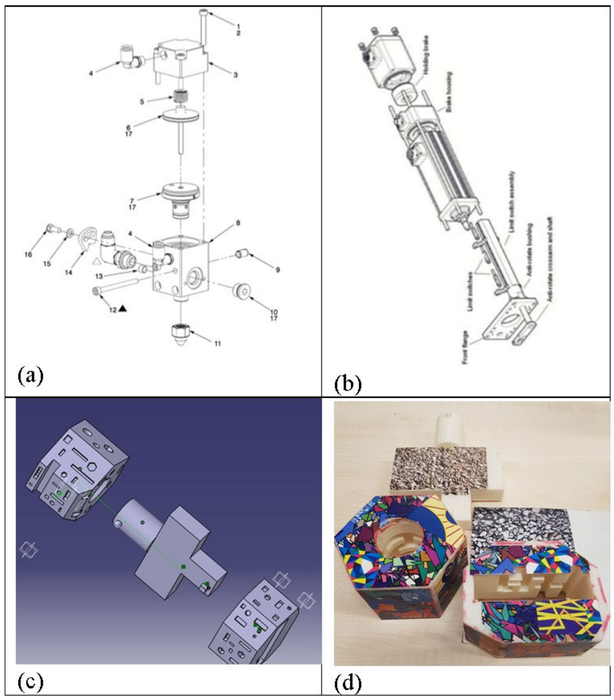

FIGURE 6. Mock-up designed for testing purposes.

C. FARA IMPLEMENTATION

This section describes how the FARA method has been implemented as a software unit in an AR system. This has been done for validating the FARA method within this study, but its implementation can be different in terms of Hardware and Software for other research or industrial purposes.

1) HARDWARE

This section describes the hardware of the AR system where FARA has been implemented and become a FARAIS. These are shown in Fig 1. FARA requires hardware with input/output capabilities. FARAIS has to collect data from the proposed environment and transfer the processed information to the operator through the output device. In this specific case, an RGB camera and touchscreen are used as the input device and a display as the output device; both are installed on most of the commercial mobiles available, i.e., the Samsung Galaxy S8. Moreover, the display has been fitted on a headset developed by XVENO. It has to be mentioned that, even though the software has been designed for these specific input/output characteristics, FARA's method could be utilised with different sensors and devices. For instance, rather than capturing the current environment with an RGB camera, it could use a depth camera and infrared cameras. The input device could consist of a laptop or a head-mounted display (HMD). As an example, Microsoft Hololens or Epson Moverio HMDs could be used to meet these characteristics. As an input device, it is not unexpected that depth sensors will be soon utilised for more efficient object recognition and tracking. In the same way, see-through displays will soon be preferred to the video see-through display utilised in this example. Finally, a virtual server has been set up utilising XAMPP.

2) SOFTWARE

The AR system software and FARA software unit have been developed together as a tablet/mobile-based application which mainly carries out three duties/units:

- Hardware control
- Data processing and storage unit
- Provide a responsive user interface (UI)

It has been developed utilising Unity3d as a game engine and Vuforia SDK and Android SDK. Moreover, a local virtual server with an SQL DB has been set up to, not only provide storage for the information collected but also process them offline easing the workload of the mobile device.

V. ANALYSIS AND RESULTS

This section reports the analysis and test results described in Section IV. Firstly, the results of the quantification test are reported in Section V-A. Then the results of the comparison with the current AR system's performances in maintenance are shown.

A. QUANTITATIVE TEST

This section reports the results of the quantification test which aims to quantify the improvements due to the utilisation of FARAIS vs hard-copy manuals as support for carrying out MRO operations. A total of 30 participants (18m/12f) took part in the study. These include students, staff, and industrial personnel. The average age was 28.8 (20, 36, SD = 4.28). The participant's background has been assessed mainly through the inclination questionnaire. None of the participants was working in maintenance. Because of the first inclination questionnaire, half of them have been asked to perform the test as CC and half as CT. Each test took from 35 to 65 minutes to complete and included the execution of an average of 3 randomly chosen tasks per participant. The data collected has been stored in compliance with Cranfield's research ethics policy. The following subsections report the statistical analysis and the results for the dependent variables "completion time" and "the number of errors" affected by the utilisation of the FARAIS support vs. hard-copy manual support.

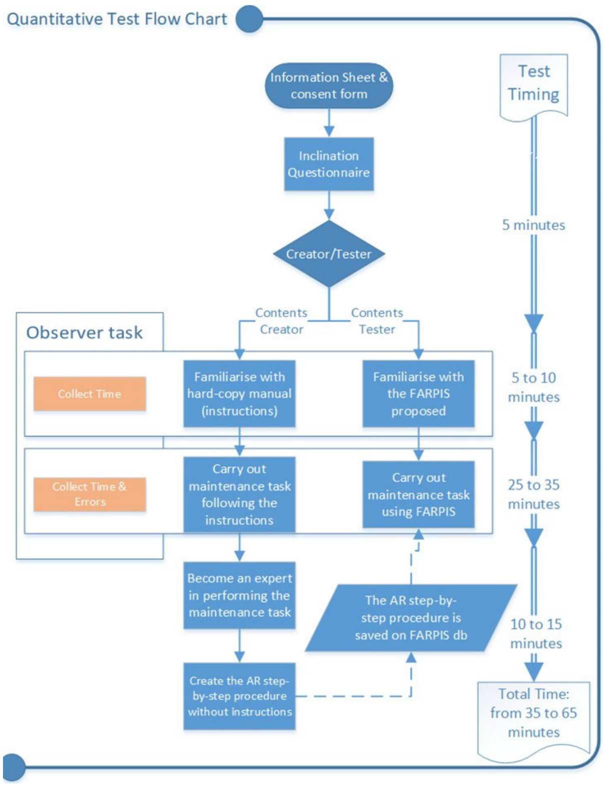

FIGURE 7. Schematic representation of the validation test.

1) COMPLETION TIME

To understand whether there is a statistically significant difference between the means of timely completion of the maintenance tasks performed using FARAIS support vs hard-copy manual, the author decided to carry out the one-way ANOVA test. The two different supports, as described in section IV-A are 1) Hard-copy manual instructions, and 2) FARAIS. The maintenance procedures tested are:

- Task 1: Assembly of the Board into the Basement
- Task 2: Assembly of the Top on the Board
- Task 3: Disassembly of the Top from the Board
- Task 4: Disassembly of the Board from the Basement
- Overall Task: The complete assembly and disassembly of the product. (Task1 + Task2 + Task3 + Task4)

The number of tasks and their characteristics has been chosen based on the case study described in Section IV-B and the authors' experience. To apply ANOVA to a sample, the normality and homoscedasticity of the latter must be validated. Even though it is generally correct to make

TABLE 2. Homoscedasticity and normality test results for the completion time dataset collected in the test. Both are validated.

Task	Normality Shapiro-Wilk Test *p*-value	Homoscedasticity Lavene Test *p*-value
Task 1	Manual: 0.226 AR (FARA): 0.353	0.239
Task 2	Manual: 0.347 AR (FARA): 0.305	0.44
Task 3	Manual: 0.119 AR (FARA): 0.395	0.22
Task 4	Manual: 0.305 AR (FARA):0.846	0.446
Overall Task	Manual: 0.16 AR (FARA): 0.623	0.129

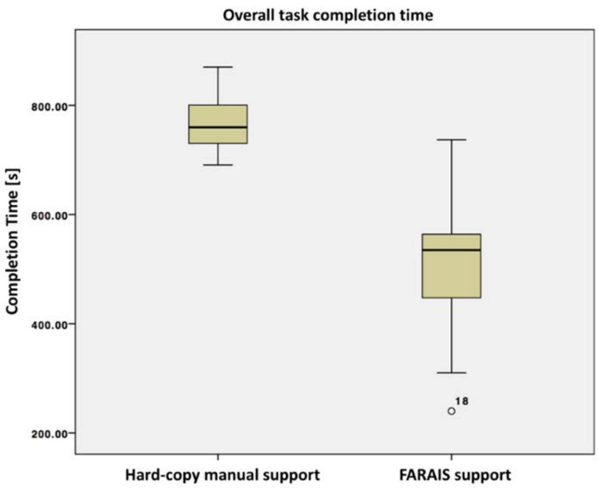

FIGURE 8. Overall task completion time with hard-copy manual and FARAIS support.

the "assume of normality" for relatively big-sized samples, in this study case it is required to validate the normality. Since the sample is smaller than 50, the Shapiro-Wilk test is carried out and each task sample results are normal since all the p values are greater than 0.05 as shown in Table 2. The homoscedasticity of the sample has been validated by applying the Levene test. Also, in this case, the p values resulted are greater than 0.05 hence the samples have the same variance.

No sample has been removed from the dataset after these tests. The analysis of variance showed that the effect of the support method on the overall task completion time is significant, F (1,28) = 32.013, $p \leq 0.05$ (95% confidence). Utilising FARAIS improves the completion time of the overall task by 34.7% (501s vs 768s) compared to the hard-copy manual support. Similarly, each task separately showed improvements in time completion. More specifically: Task1 - F (1,28)=39.793, $p \leq 0.05$ - 55.3% (79s vs 177s).

2) NUMBER OF ERRORS

The approach utilised for analyzing the number of errors collected is the same as the one utilised for analysing the completion time described in the previous section. In performing the normality tests of the error datasets, it has been found that the data collected regarding the errors performed in the single tasks are not normally distributed because these did not pass the normality test. As shown in Table 3, the p-values calculated through the Shapiro-Wilk test for the errors related to Task1, Task2, Task 3, and Task 4, are smaller than 0.05. Thus, applying the ANOVA test to single-task datasets has not been possible. On a positive note, the overall task error dataset resulted to be both normally distributed and homogeneous in terms of variance.

TABLE 3. Homoscedasticity and normality test results for the number of errors dataset collected in the test. Normality and homoscedasticity are verified only for the overall task.

Task	Normality Shapiro-Wilk Test *p*-value	Homoscedasticity Lavene Test *p*-value
Task 1	Manual: 0.003 AR (FARA): 0.000	0.749
Task 2	Manual: 0.001 AR (FARA): 0.000	0.066
Task 3	Manual: 0.000 AR (FARA): 0.000	0.394
Task 4	Manual: 0.042 AR (FARA):0.000	0.052
Overall Task	Manual: 0.673 AR (FARA): 0.126	0.2

TABLE 4. Quantitative test results summary.

Task	Time reduction (%)	Error reduction (%)
Task 1	55.3	-
Task 2	29.4	-
Task 3	34.7	-
Task 4	24.7	-
Overall task	34.7	68.6
Average	35.8	68.6

Due to this above, the ANOVA test has been performed only for the overall task errors. The analysis of variance showed that the effect of the support method on the overall task number of errors is significant, F (1,28) = 30.919, $p \leq 0.05$ (95% confidence). Utilising FARAIS decreased the number of errors of the overall task by 68.6% (1.53 vs 4.87) compared to the hard-copy manual support.

B. QUANTITATIVE COMPARISON OF RESULTS

This section reports the comparison between AR systems reported in the literature and FARAIS in which the validation results are presented in Section V-A. The quantitative performance results of FARAIS for time and error reductions are summarized in Table 4. The results have been collected by applying the empirical test methodology described in Section IV and reported in detail in Section IV-C. These can be qualitatively compared with the ones found in the literature. The latter reports the results of the literature studies which compared the utilisation of AR systems for supporting maintenance (designed and tested within their projects) vs the utilisation of hard-copy manual supports.

It has to be mentioned that not all the studies which propose an AR application for maintenance report in detail the time and error reductions (AR vs. hard-copy manual) as well as the insight of the methodology and testing material utilised for collecting the data and analysing it. For instance, some authors clearly explain the methodology utilised for validating a large-screen AR application [28]. In the study, the independent variables have been the instruction mode (paper vs. AR) and the task. Measures have been carried out on completion time and errors. Still, the reader does not have access to the complete paper instructions or AR step-by-step procedure. What kind of information has been provided to participants to perform the maintenance task with the paper instructions? Was there a lot to read which could have affected the completion time? Were the instructions clear or this could lead to misinterpretations? How were the AR instructions displayed? Similarly, others have outlined a validation methodology with four instruction modes utilised [29]: printed manual, LCD instructions, HMD AR and spatially registered AR. Still, not having access to the actual instructions makes it difficult to understand whether their structure and contents could have affected the test results. Therefore, it would not be accurate to quantitatively compare the literature outcomes with this study's results which might have used different user-AR interfaces and printed manual levels of detail. For this reason, the authors of this study decided to do a qualitative comparison of the results against others similarly published research in the literature. More specifically, the qualitative comparison is made with the eight studies which the authors considered to have more similarities in terms of field of application and validation procedure.

TABLE 5. Maintenance performance improvements in terms of time and errors reductions found in the literature.

Reference	Task	Time reduction (%)	Error rate reduction (%)
[30]	Assessing spart parts	45	-
[28]	Diassembly	38 (22.4 min)	92.4 (87.5 min)
[31]	Aircraft maintenance	50	-
[32]	Notebook Diassembly	7	70
[19]	Task localisation	46.7	-
[29]	Puzzle, disassembly	26	82
[4]	Inspection	50 to 66	-
[33]	Accessing info	16	42
Average		35.5	71.6

By qualitatively comparing the performance in Table 5, it is possible to understand that the performance of FARAIS is close to other reported AR systems in the literature. The time reduction calculated for FARAIS is close to the average time reduction shown in previous studies and listed in Table 5. More specifically in this study, the average time reduction is around 36% (Table 4). The average time reduction of referenced studies (Table 5) is 35.5%. It is interesting to note that Fiorentino et al observed a time reduction close to the one observed in this study [28]. It might be because the assembly task utilised for testing purposes presents

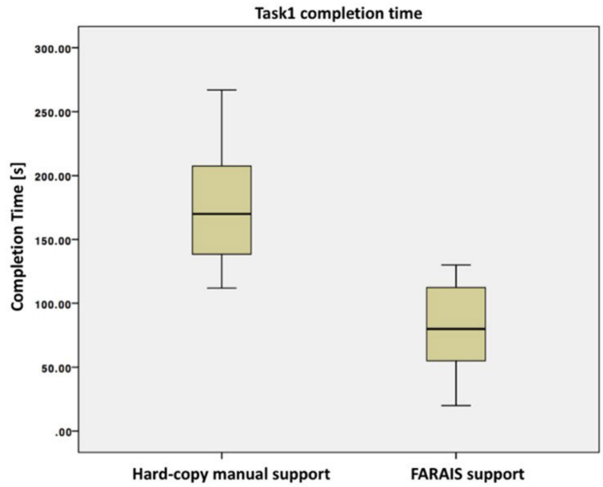

FIGURE 9. **Task 1 completion time with hard-copy manual and FARAIS support.**

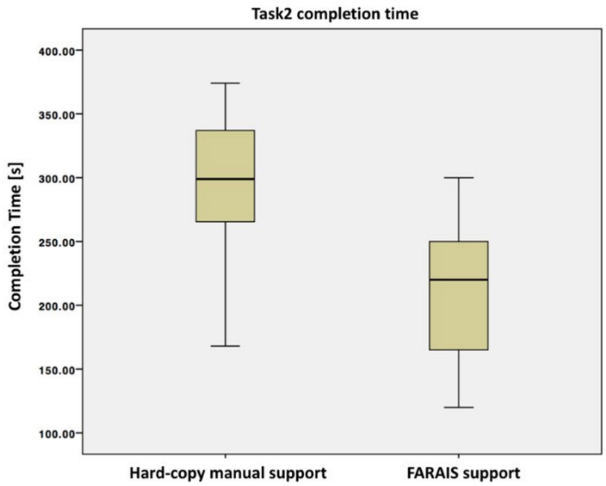

FIGURE 10. **Task 2 completion time with hard-copy manual and FARAIS support.**

similarities with the one proposed in this study since both concern mechanical components with axial and rotating movements involved. Ong et al [4] and Sanna et al [32], had reported time reductions from 36%. The tasks involved in their studies were notebook disassembly and inspection operation. These hardly relate to the mockup utilised in this work and are shown in Section IV-B. FARAIS error reduction calculated is around 70% (Table 4). The average time reduction in Table 5 is about 72%. Not all the studies which observed and reported the time reductions also observed or reported the errors reductions. The systematic observation of the errors occurring in a maintenance operation requires a methodology which lists in detail how and when an error should be detected. In this study the author designed in the mock-up design, three dis/assembly errors explained in Section IV-B.

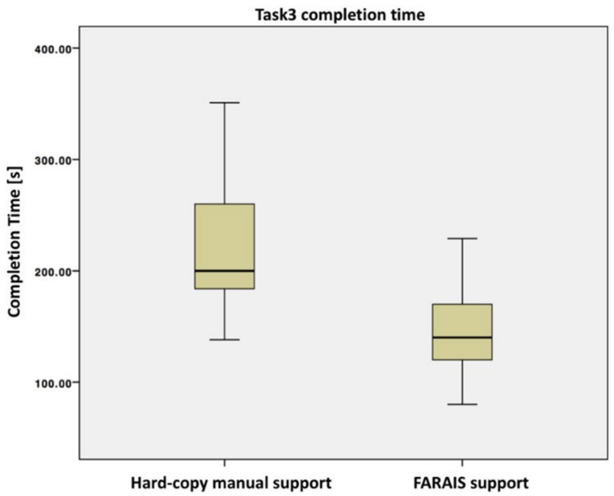

FIGURE 11. Task 3 completion time with hard-copy manual and FARAIS support.

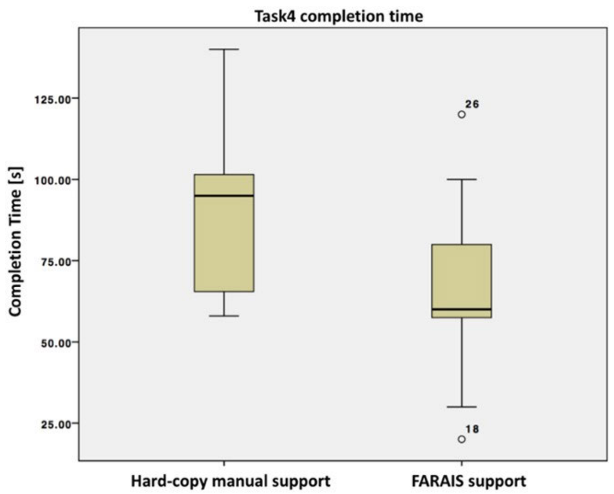

FIGURE 12. Task 4 completion time with hard-copy manual and FARAIS support.

VI. DISCUSSION

The authors' intent in developing FARA is to provide a method for allowing technicians to create AR-based maintenance step-by-step procedures while performing the task and with minimum effort. FARA is developed based on two assumptions: 1) To have robust and reliable object tracking and recognition; and 2) When CAD models are available. The authors believe that both these assumptions will be validated in the near future. The current research effort is working on object recognition and tracking solutions which, through the utilisation of new sensors and technology (depth cameras, point cloud, etc.) will overcome current lighting, occlusions, and background noise issues. As AR technology gets more matured over time so does the tracking system and the use of 3D models for visualization purposes. Therefore, there will be no additional hardware for implementing the FARA

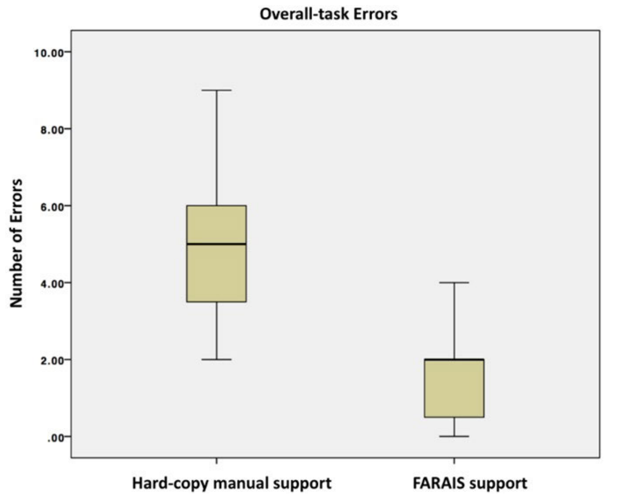

FIGURE 13. Overall task number of errors with hard-copy manual and FARAIS support.

method but an algorithm (FARA method) that automates the authoring process from the tracking data. The setup is progressively being reduced as the advancement in AR technologies are advancing. It must be mentioned that one limitation of FARA and in general of AR systems will remain the recognition of similar and symmetrical objects which have a different internal composition (e.g., two spheres with different weights but the same radius). Furthermore, registration also poses an important issue in AR, particularly in handling occlusion between real and virtual objects. In an AR environment, improper occlusion can hinder process efficiency rather than enhance it. The utilisation of multiple cameras could be a potential workaround for this issue. The second hypothesis can be considered generally true for the industrial environment. FARA has been described as a method and its implementation in an AR system has been named FARAIS. The intent of having two acronyms (FARA and FARAIS) is to emphasize the difference between the method (FARA) and its actual practical utilisation once implemented in an already existing AR system (FARAIS: FARA Implemented System). Even if different FARAIS can be proposed (Section IV-C1), the authors believe that this would not negatively affect the result of the test reported in this article. The FARAIS proposed in this project has been developed to comply with the minimum requirements in terms of performance and user interface because this project aimed to validate FARA and not the AR system. This method was tested by having maintainers perform the task in front of an AR system (therefore among the other things capable of recognizing the objects) to create a step-by-step procedure which can be understood by untrained users. Ideally, if all the maintainers would use a FARAIS, lots of step-by-step procedures could be created without additional programming.

To validate FARA, the authors quantified its performance and compared it with the literature findings.

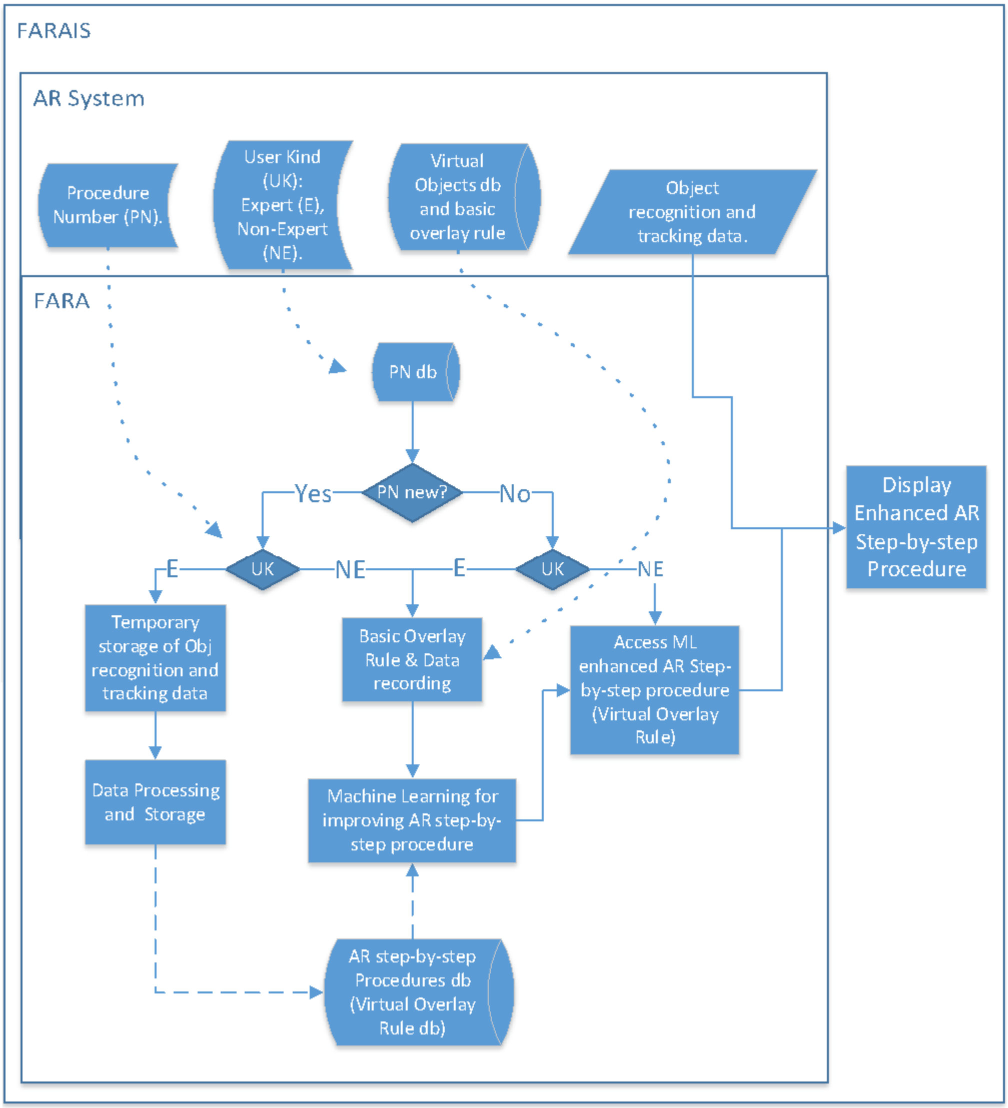

FIGURE 14. Schematic representation of the FARA method implemented with Intelligent Learning.

The methodology for quantifying the time and error reduction has been explained. It is worth mentioning that similar methodologies have been utilised by other studies [19], [28], [29]. For these reasons, even though for relatively small samples a non-parametric approach such as the Friedman test would be recommended, the authors still preferred to assume normality and homoscedasticity based on previous results. The average time reduction in performing the test's maintenance tasks in Section V-A1 (FARAIS vs hard-copy manual support) is 35.8%. The biggest time reduction has been observed in Task 1, followed by Task 3, Task 2, and Task 4. The authors believe this is because the participants who had to perform Task 1 with the hard-copy manual needed to take confidence in the manual itself. On the other side, the participants performing Task 1 with FARAIS intuitively followed the instructions on the screen.

The average error reduction (FARAIS vs hard-copy manual support) is 68.6%. It has not been possible to calculate the error reductions of the single tasks because the hypothesis of normality and homoscedasticity were not verified. It has to be considered, for future studies, the need of implementing more variance in terms of errors collected. This could be achieved by testing longer maintenance tasks or artificially creating more tricks for the study participants. It must be mentioned that the case study utilised for validation is limited to an assembly and disassembly procedure and does not validate FARP in other maintenance operations. However, the application of the FARP method for repair, inspections, and overhaul operations seems feasible and needs further investigation. The FARA method can be improved to detect assembly/disassembly errors to inform the AR user regarding the correct procedure (e.g., misalignments). In addition, this method is currently more suited to maintenance applications because the mechanical part is more likely to have its CAD model available.

The methodology for comparing FARA's performance results is not as strict as the quantifying one. This is due to that not all the studies about AR application in maintenance have as results a quantified time saving and error rate number. Based on the author's experience, the results of the comparison test can still be considered satisfying. It must be said that, for more effective validation of FARA as an authoring method, it should have been directly compared with the authoring methods developed by other research centres and applied to the same case study. Unfortunately, this process would have required, not only access to the conceptual authoring methods but also access to the actual tool that different research centres have utilised for the validation. This includes software and hardware. This approach for validating FARA seemed impractical and not suitable at this stage of the study. Therefore, to have a comparative evaluation of the AR system across different studies with traditional methods, there is a necessity in creating a standard for the components to be assembled (e.g., a mockup) and the assembly manuals for a particular task that will be compared against an AR solution. The authors have included materials in this article that are used to test this approach such as paper-based manuals that describes the task being tested and 3D models. In this way, it is possible to have a fair comparison by replicating the task and comparing the efficacy of FARA implementation with other types of authoring systems. Nevertheless, since FARA implementation enables "task recording" for building step-by-step instruction, it could be hypothesized that there is much more time saving gained in comparison to any other platforms that require time spent in programming or developing AR step-by-step instruction.

VII. CONCLUSION

FARA is a geometry-based method for authoring AR content for maintenance. It is based on two assumptions: 1) machines can recognise the objects in a working environment, and 2) CAD models are available for all the real objects involved in the maintenance procedure. FARAIS is intrinsically not time-consuming and not tedious since it does not require the maintainer to do anything, but only perform the maintenance task. At the same time, it can provide a similar amount of time and error reductions as other AR systems for maintenance. For these reasons, the authors consider FARA as a step forward in the development of authoring solutions for AR (for maintenance but not only). It does not require any programming skills to be operated. FARA has been presented and its validation has been reported in this article. The proposed method can be applied to any AR system and has to be implemented as a software unit. To the best of the authors' knowledge (literature and experiences) it is the only method that allows users to create AR step-by-step procedures with minimum effort. It will be sufficient to run the application and the transformations in space of the objects in the FOV will be recorded and utilised to automatically build the AR maintenance procedure. This can then be accessed by a non- expert user to carry out the same operation. Future studies should aim for more testing that represents the actual industrial case study to test the usability of the FARA method. The objective of the study should expand validation and take more advantage of the information recorded. The validation also needs to consider both the learning time and the time required for creating an AR step-by-step procedure. The first consists of the time a maintainer needs to gain confidence with FARA and create AR procedures. It should be compared with the time required for learning how to use other authoring tools available. The time required for creating AR procedures, on the other side, should be quantified by collecting the time required when utilising FARA and when utilising other authoring tools but all applied to the same case study. Figure 14 shows the planned expansion of the method. Comparing this with the current schematic representation of FARA, it is possible to see one new process: Machine Learning (ML) for improving AR step-by-step procedures. Furthermore, AR should not be limited to animation overlay only. The approach needs to be formalized into a software package which can easily integrate with existing AR authoring tools to enrich the informativeness of AR procedures. For example, automated arrows to show the direction and rotation, text boxes for enriching each step with descriptions, pdf links for opening manuals, and vocal indications to support the operation. The idea should be to utilise the data collected during any maintenance procedure for automatically creating and/or enhancing the AR step-by-step procedures. By the application of intelligent learning, FARA could potentially, classify the MRO operation steps and propose a different solution to a similar maintenance problem, without the need for expert training. Finally, future works should remove the assumptions made at the outset of this study and more validation should be performed on various maintenance scenarios.

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RICCARDO PALMARINI received the M.Sc. degree in aircraft vehicle design from Cranfield University and the Ph.D. degree from Cranfield University, in 2019. He is currently working as an Instrument and Automation Engineer at TechnipFMC. His Ph.D. project focused on developing an augmented reality (AR) based on visualization system to support with the delivery of maintenance and manufacturing.

IÑIGO FERNÁNDEZ DEL AMO received the degree in industrial engineering from the Polytechnic University of Madrid (UPM), in 2016, the degree in manufacturing consultancy from Cranfield University, in 2016, and the Ph.D. degree from Cranfield University. He received the scholarship from Babcock International for his Ph.D. degree. His primary interest is to study innovative software methods to capture maintenance experts' knowledge and reduce the cost of AR's industrial implementation. Besides his Ph.D. research, he has co-supervised various M.Sc. thesis and group projects that involve the implementation of AR and digital twins in the industrial workplace using SW technologies. His overall aim is to enable the transformation of operative roles into a source of valuable information for through-life engineering services using innovative visualisation and data-structuring technologies. His research interests include the use of augmented reality (AR) and semantic web (SW) for knowledge capture in maintenance diagnosis. He won the 2017 Cranfield Vice-Chancellor's Prize for being the most outstanding M.Sc. student.

DEDY ARIANSYAH worked previously as a Research Fellow at Cranfield University, under the EPSRC-funded project DigiTOP, where his research focused on how immersive technologies like augmented reality can improve industrial productivity and digital twin development to support decision-making. He is currently involved in the AI Research Team, where he focuses on the embedded AI in immersive technologies and knowledge capture to improve task productivity, increase the efficiency of knowledge transfer, and data-driven process optimization. His Ph.D. degree was focused on the virtual reality driving simulator for driver behaviour analysis, where he developed and integrated physiological data and driving performance to study different human cognitive operations when interacting with driver assistance systems.

SAMIR KHAN (Member, IEEE) received the B.Eng. and Ph.D. degrees from Loughborough University. He is currently a Senior Lecturer often collaborating with Rolls-Royce, Jaguar Land Rover, BAE Systems, and MoD. His research interests include intelligent monitoring, AI-based control, perception, and planning in the context of autonomous systems and service robots, with a focus on the embedded hardware implementation of machine learning techniques for anomaly detection and prognostics and system health management, development of the IoT technologies, digital twins for maintenance decision making, and intelligent monitoring of intermittent failures and false alarms in electronic systems. He is a Chartered Engineer and a member of IET.

JOHN AHMET ERKOYUNCU received the Ph.D. degree in uncertainty modeling for maintenance from Cranfield University, in 2011. He is currently the Head of the Digital Engineering and Manufacturing Centre. He is active with Innovate U.K. and EPSRC-funded projects around research topics: digital twins, augmented reality, digitization (degradation assessment), and simulation of complex manufacturing and maintenance procedures. He is a Chartered Engineer, an Associate Member of CIRP, and the Co-Chair of the Through-life Engineering Services Council.

RAJKUMAR ROY received the B.Eng. and M.Eng. degrees in production engineering from Jadavpur University, India, and the Ph.D. degree in computing from the University of Plymouth, U.K. 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. He joined the City, University of London from Cranfield University, where he was the Director of Manufacturing. His 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. He is the Founding Editor-in-Chief of the *Applied Soft Computing* journal (Elsevier); and a fellow of CIRP (International Academy for Production Engineers), the Institute of Engineering Designers (IED), and the Higher Education Academy (HEA).