CRANFIELD UNIVERSITY

Riccardo Palmarini

Authoring digital contents for Augmented Reality in Maintenance

School of Aerospace, Transport and Manufacturing

PhD
Academic Year: 2015 - 2018

Supervisor: Dr. John Ahmet Erkoyuncu
Associate Supervisor: Prof. Rajkumar Roy
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ABSTRACT

Technicians' performance is a major driver in maintenance and each process can be prone to time and quality variances as well as errors due to factors such as experience, complexity and environment.

Augmented Reality (AR) is an emerging technology that has been applied in a wide variety of disciplines and has been demonstrated to have a role with improving efficiency, effectiveness and decision-making within industrial maintenance. AR has not reached its full potential yet and its implementation in Industry is slowed down by three main limitations: hardware restricted capabilities, object recognition robustness and contents-related issues.

This PhD project focuses on easing the implementation of AR by overcoming the AR technology selection challenges and the AR contents-related issues. In order to reach the aim, the student has provided three main contributions to knowledge: 1) a process to select AR technology for maintenance (IPSAR), 2) a method for creating AR step-by-step procedures (FARP) and 3) a method for providing remote assistance (ARRA).

FARP and ARRA methods have been developed and tested. The first allows recording procedures in an ad-hoc designed "AR-format" and is able to show "step-by-step" procedures. It aims to support deskilling the maintenance process and reducing the error rate by simplifying the delivery of maintenance with efficient and effective guidance. The second overcomes current remote video-call assistance limitations by improving spatial referencing. ARRA module allows to provide AR-assistance by overlaying virtual objects on the real environment of a remote maintainer.

The methods proposed by the student could boost the implementation of AR and open the doors for a bright future in which AR supports technicians thus reducing operational costs and training and improving human performances.

Keywords:

Augmented Reality, Maintenance, Authoring, Ergonomics, Human performance.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACW: AntiClockWise

AI: Artificial Intelligence

ANOVA: ANalysis Of VAriance

AR: Augmented Reality

ARRA: Augmented Reality for Remote Applications

BAS: Building Automation System

CAD: Computer Aided Design

CAM: Context-Awareness Module

CC: Contents Creator

CDF: Context-Data Framework

CMMS: Computerized Maintenance Management System

CT: Contents Tester

CW: ClockWise

db: database

E: Experienced

EC: Exclusion Criteria

FARP: Fast Augmented Reality Programming

FARPIS: FARP Implemented System

FOV: Field Of View

GPS: Global Positioning System

HD: High Definition

HMD: Head Mounted Display

IC: Inclusion Criteria

IPSAR: Innovative Process for Selecting Augmented Reality

IT: Information Technology

KB: Kilo Bytes

KPI: Key Performance Indicators

LHC: Large Hadron Collider

MID: Mobile Internet Device

MRO: Maintenance, Repair and Overhaul

NE: Not Experienced

O&M: Operations and Maintenance

PDF: Portable Document Format

PICOC: Population, Intervention, Comparison, Outcomes and Context

PN: Procedure Number

POV: Point Of View

QC: Quality Criteria

RA: Remote Assistance

RGB: Red Green Blue

RODOF: Real Object Degrees Of Freedom

ROI: Return On Investment

SDK: Software Development Kit

SIFT: Scale Invariant Feature Transform

SLR: Systematic Literature Review

SQL: Structured Query Language

SURF : Speed Up Robust Features

UI: User Interface

UK: User Knid

VODOF: Virtual Object Degrees Of Freedom

VPA: Value Proposition Analysis

VR: Virtual Reality

LIST OF PUBLICATIONS

R. Palmarini, J. A. Erkoyuncu, and R. Roy, “An Innovative Process to Select Augmented Reality (AR) Technology for Maintenance,” in *Procedia CIRP*, 2017, vol. 59, pp. 23–28.

R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi, “A systematic review of augmented reality applications in maintenance,” *Robot and Computer-Integrated Manufacturing*, vol. 49, no. February, pp. 215–228, Feb. 2018.

R. Palmarini et al., “Designing an AR interface to improve trust in Human-Robots collaboration,” *Procedia CIRP*, vol. 70, pp. 350–355, 2018.

R. Palmarini, J. A. Erkoyuncu, R. Roy and I. Fernández del Amo, “Fast Augmented Reality Programming : fats creation of AR step-by-step procedures for maintenance.” – submitted to *Computers in Industry*.

R. Palmarini, J. A. Erkoyuncu, R. Roy and I. Fernández del Amo, “Augmented Reality for improving spatial referencing in Remote Assistance: ARRA” – ready for submission.

1 Introduction

"Augmented Reality (AR) is a digital technology which empowers at the same time:

1) human senses through the utilisation of sensors,
2) human cognition through the utilisation of virtual objects

It aims to improve human performances and safety in carrying out specific activities, real time."

The definition provided above is proposed by the author of this study. The author decided to put the human in the centre of the definition and tries to avoid ambiguities with other digital support systems.

Without this definition, in fact, we could think, for instance, that a robot utilises AR for identifying an object through cameras and taking actions as programmed. The autopilot of an aircraft might seem to work through AR because it changes the route of the plane based on the sensors' inputs and navigation programme. The parking alarm of a car or the calendar popping up a notification regarding a meeting could be thought as a tool that augments the human perception of spaces and time.

AR should not be confused with the technologies mentioned above. AR is a technology that utilises the data captured through sensors, transforms it into knowledge and transfers it to humans by the utilisation of ad-hoc created virtual objects which overlay on the human's reality improving his/her understanding of the. AR always leaves to humans the last word on the actions to be taken. This is essential because, today, humans still have one big advantage on machines: humans know how to act in case of an unpredicted event.

1.1 Project Overview

This project investigates into the application of AR on maintenance operations and focuses on the development of new methodologies for overcoming one of the main obstacles that are currently preventing AR technology from its industrial application: the selection of AR for maintenance applications and the creation/management of the digital contents for AR. These obstacles have been identified as such as a result of a detailed Systematic Literature Review (SLR) which is reported in chapter 2.

At the current stage, in fact, AR in maintenance has been proven to be very effective in terms of time savings, error reductions and safety but mostly at an academic level [1]–[3]. The author believes that providing a method for the easy creation of the contents for AR ("authoring" of the contents for AR) and its management would result in accelerating the implementation of AR in industry.

The "AR contents" consist of the asset of digital information which needs to be created (if not available) and "aligned" with the real environment. By "aligned" it is meant the process of associating each digital content with the correct real object/environment in both space and time. In the current state of the art, several professional figures (programmers, animators, CAD modeller) are required for developing the required AR contents.

Figure 1.1 is proposed to better let the reader understand what this project is about. On the top left, it is possible to see a mobile device pointing at a metallic box in which is placed an electronic board. In order to assembly the electronic board, the technician has to fasten a nut utilising a wrench. The AR application shown overlays the virtual wrench over the real box and electronic board. More specifically, when pointing the mobile device, the RGB camera transmits the data to the processor of the mobile which then, through the AR pre-determined rules, shows on the display the virtual wrench aligned with the nut and rotating for simulating the tiding up action. The technician should follow the simulation and carry out the maintenance operation. The technician can advance in the simulation by pressing the "Next" button on the top right corner to see the next animation. He is also allowed to navigate backward by pressing the "Prev." button on the top left corner to see the previous animation.

In the case shown in Figure 1.1, the animations and the alignment rule have been implemented manually as commonly done nowadays in AR. It is not enough, in fact, to have the CAD models. The way these CAD models have to be overlaid over the real objects recognised by the RGB camera, their relative position with respect to the camera and the direction of the animations showing the maintenance procedure have to be designed and implemented by AR experts, maintenance experts, animators, CAD modellers and programmers. This results in an expensive and time-consuming process for creating contents for AR in maintenance.

Moreover, there is a need of collaboration between the industrial/maintenance expert and the AR expert also when selecting the technology required (hardware and software) for implementing an AR maintenance support system.

Therefore, this project aims to ease the implementation of AR in industry by reducing the number of professional figures required for selecting, developing and managing AR contents for maintenance.

More specifically this project tries to provide an alternative answer to the questions reported in Figure 1.1 (see red boxes) and overcoming the current need of several professional figures (*"Current Practice Answer"* in Figure 1.1) and time consuming processes.

The author, in fact, proposes FARP - Fast Augmented Reality Programming (chapter 4) and ARRA - Augmented Reality for Remote Applications (chapter 5) as two methods which intend to overcome the contents-creation issue for both the on-site maintenance and the remote assistance scenarios (*"This Project Answer"* in Figure 1.1).

Moreover, an industry approaching AR does not have a tool for understanding whether or not AR is required and what kind of investment would be needed for implementing AR in his/her value-chain. Even though this study does not investigate into the economic aspects of utilising AR, still it proposes a method for selecting the technology required for specific applications (chapter 3)

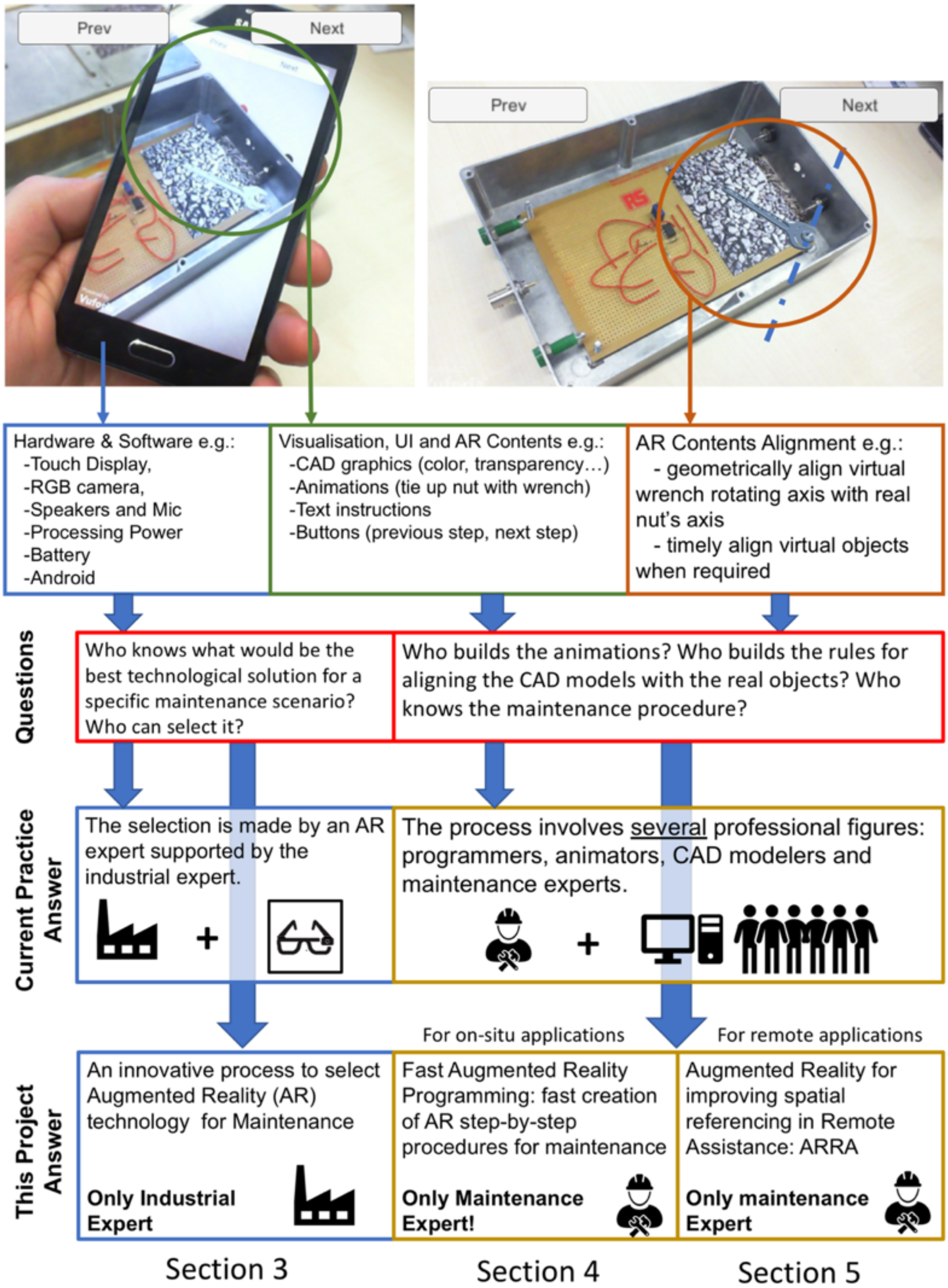


Figure 1.1 Project overview infographic.

1.1.1 Aim and Objectives

The aim of this project is:

To develop an automated geometrical-based method for creating AR contents in maintenance thus easing AR implementation in Industry.

In order to achieve the aim, the author has set different objectives:

1. Conduct a SLR around the implementation of AR in maintenance. This includes topics such as: image processing, marker-less recognition, object recognition, software development.
2. Propose a method for selecting AR technology (including hardware, development platform and visualisation method) for specific maintenance applications. The method has to provide an answer to the following 4 questions:
3. Develop a method for automatically creating AR contents for maintenance concerning on-site activities
4. Develop a method for allowing AR remote assistance for improving spatial referencing.

Where by method is intended a replicable systematic approach, which does not rely on the currently available technology or the technology utilised in this study for validation purposes.

1.1.2 Thesis structure

This thesis project is proposed in the "paper format" in agreement with Cranfield University policy. The fulfilment of each one of the objectives (a-d) mentioned in the previous sec. 1.1.1 is proposed as an individual paper chapter which contains all the aspects required to describe that specific package of work including an introduction, methodology, results and discussion. Still, in order to provide a unified coherent document, the author has provided the scheme below (Figure 1.2) which aids visualisation of connections between the paper chapters.

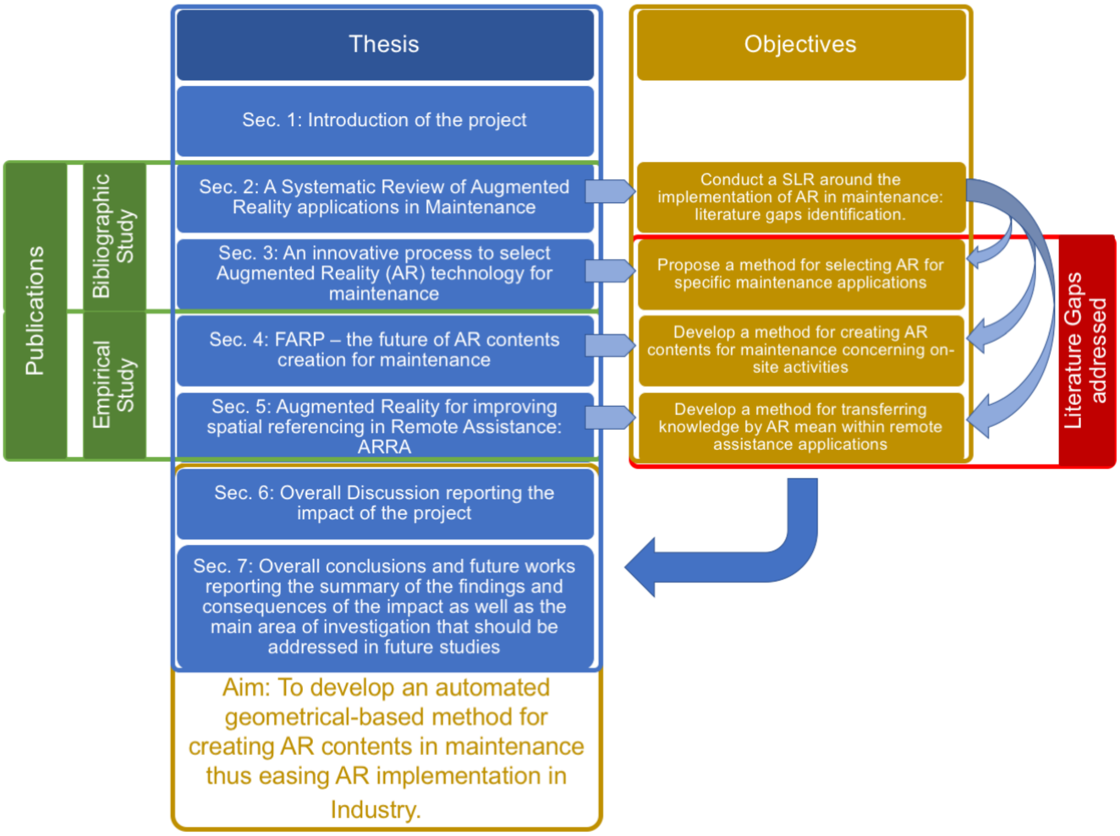


Figure 1.2 Diagram showing the link between the objectives (on the right), the thesis sections (in the middle) and the scientific publications (on the left).

Therefore, the thesis is structured as follows:

- Chapter 2 reports the SLR which reveals the gaps found in literature an puts the bases for this research project. The SLR journal paper has been published by "*Robotics and Computer-Integrated manufacturing*" in 2018 under the title: "*A systematic review of Augmenter Reality application in Maintenance*".
- Chapter 3 addresses the first gap found in literature proposing a method for selecting AR for maintenance: IPSAR. The paper has been published by Elsevier for "*The 5th International Conference on Through-life Engineering Services (TESConf 2016)*"
- Chapter 4 is the individual paper chapter which proposes FARP (Fast Augmented Reality Programming): geometrical based method for creating AR contents for maintenance. The journal paper has been submitted to

"*Computers in Industry*" and revision has been requested. The paper has been resubmitted on October the 4th 2018.

- Chapter 5 reports the individual paper chapter which proposes ARRA (Augmented Reality for Remote Applications). The paper is ready for submission.

Each section has its own abstract, introduction, background review, methodology, results, discussion and conclusions. Each chapter's discussion and conclusion concern the specific aspects included within the chapter. The overall discussion (chapter 6), the overall conclusions and future works (chapter 7) provide a supplementary overview of the project as a unified and coherent piece of work. More specifically:

- the overall discussion (chapter 6) reports the impact of the project and the future potential of the AR technology within maintenance
- the overall conclusions and future works chapter (chapter 7) summarises the findings and the project final outcome. Moreover, future field of investigations that should be addressed to fulfil the remaining AR gaps and overcoming this research limitations are suggested.

2 A Systematic Literature Review (SLR) of Augmented Reality applications in Maintenance

Abstract. Augmented Reality (AR) technologies for supporting maintenance operations have been an academic research topic for around 50 years now. In the last decade, major progresses have been made and the AR technology is getting closer to being implemented in industry. In this chapter, the advantages and disadvantages of AR have been explored and quantified in terms of Key Performance Indicators (KPI) for industrial maintenance. Unfortunately, some technical issues still prevent AR from being suitable for industrial applications. This chapter aims to show, through the results of a systematic literature review, the current state of the art of AR in maintenance and the most relevant technical limitations. The analysis included filtering from a large number of publications to 30 primary studies published between 1997 and 2017. The results indicate a high fragmentation among hardware, software and AR solutions which lead to a high complexity for selecting and developing AR systems. The results of the study show the areas where AR technology still lacks maturity. Future research directions are also proposed encompassing hardware, tracking and user-AR interaction in industrial maintenance is proposed.

2.1 SLR Introduction

Milgram and Kishino [4] define Augmented Reality as a way to “augment” the real-world with virtual objects. More specifically Azuma [5] defined the AR Systems to have the following properties: to combine real and virtual objects in a real environment; run interactively and in real time; to geometrically align virtual objects and real ones in the real world. AR technology has been applied to a wide range of fields: tourism, entertainments, marketing, surgery, logistics, manufacturing, maintenance and others [6], [7]. Its application in the maintenance field has shown several advantages at an academic level.

Maintenance covers all the actions, which aim to restore any functionality of a product within its lifecycle. When the product is an industrial production equipment, we usually refer to its maintenance as industrial maintenance. The actions that can be performed to restore products’ functionalities can be technical, administrative and managerial [8].

AR studies in maintenance show promising results in enhancing human performance in carrying out technical maintenance tasks, improving the administration of maintenance operations and supporting maintenance managerial decision making. Even though what mentioned above and AR technology being around for more than 50 years, there are still limited examples of its concrete implementation in industry. For this reason, the aim of this chapter is to present the state of the art in AR in terms of technology used, applications, and limitations focusing on the maintenance context. In order to do so, the author carried out a Systematic Literature Review (SLR). SLR refers to a rigorous literature review which ensures the reproducibility and scalability of the study as well as the objectivity of the results [9]. This approach is particularly relevant for researches currently experiencing a fast development.

This chapter is organised in four sections. Section 2.1 introduces this SLR. Section 2.2 reports on the methodology utilised for this SLR. Section 2.3 reports on the main results of the SLR providing an overview of the state of the art of AR in maintenance and the main limitations of today's AR technology. Finally, section 2.4 reports the SLR conclusions and future works.

2.2 SLR Methodology

In order to evaluate the state of the art for AR in maintenance, a SLR approach has been used. SLR aims to search, appraise, synthetise and analyse all the studies relevant for a specific field of research.

The methodology utilised is described by Booth in "systematic approaches to a successful literature review" [10]. The main aim is to identify the gaps in literature hence provide evidence of future fields of research. The seven steps utilised to carry out this SLR are: planning, defining the scope, searching, assessing, synthetising, analysing and writing. Each step follows a specific methodology which will be described in the following subsections. The SLR methodology steps (white rectangles) and the outcomes of each step (blue rectangles) are outlined in Figure 2.1.

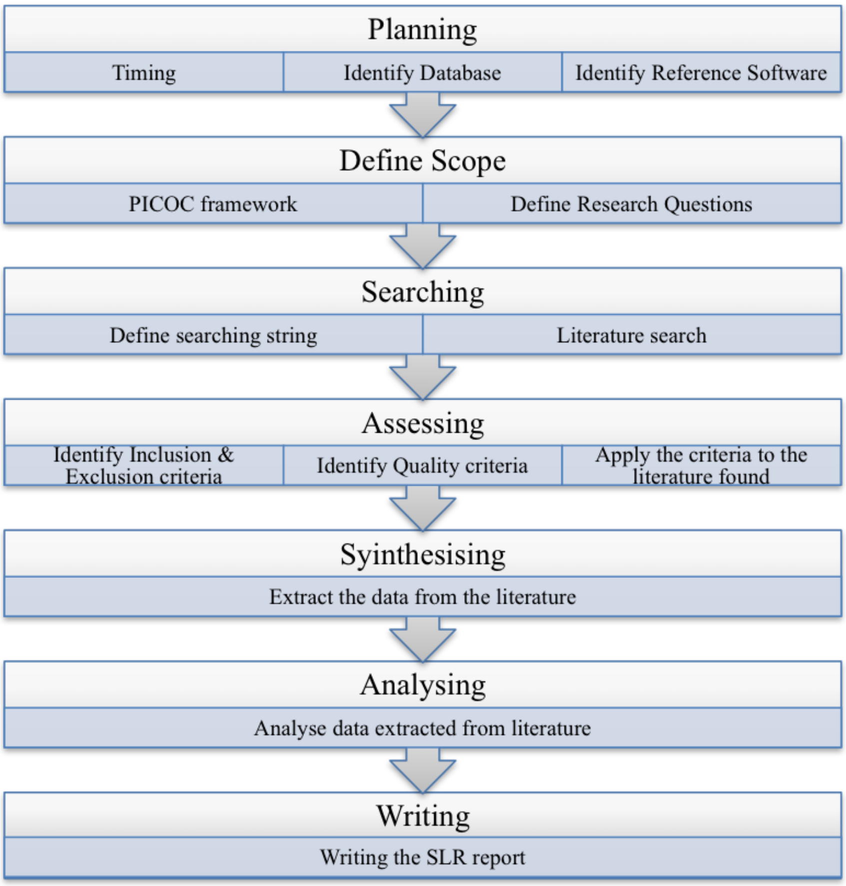


Figure 2.1. SLR methodology utilised for this SLR [10]. the 7 steps of the methodology are reported in the white rectangles . The blue rectangles show the outcomes of each step.

2.2.1 Step 1 - Planning

The planning phase is the very initial step to carry out a SLR. As shown in Figure 2.1, it includes: defining the timescale of the project, identifying the databases that will be utilised and select the software for managing the references.

The database utilised for the SLR have been selected based on [11] and integrated with the resources available for the project:

- IEEE Xplore (www.ieeexplore.com)
- ScienceDirect (www.sciencedirect.com)
- Scopus (www.scopus.com)

- Google Scholar (www.scholar.google.co.uk)

Moreover, due to the rapid evolving nature of the topic, a manual search of Grey Documentation has been performed. It includes documentation available on Internet and published by non-academic institutions such as industries, government and communities [10].

The reference manager software utilised is Mendeley *(www.mendeley.com)* due to its strong community and support, its integrated PDF viewer and the automatic citation add-in for Microsoft Word.

2.2.2 Step 2 - Defining the Scope

Defining the scope actualises in properly formulate answerable research questions. These have been defined as a result of an iterative process among *(i)* initial brainstorming, *(ii)* literature search and the *(iii)* PICOC (Population, Intervention, Comparison, Outcomes and Context*)* framework application [10]. As a result of *i and ii*, different review and key papers on AR have been identified [2], [12]–[16]. Then the PICOC framework has been utilised to define the key concepts of the research [10]. The elements of PICOC are: *Population*, *Intervention, Comparison, Outcomes* and *Context*. For this study, the *Population* consists of the industrial maintenance task carried out by human operators. The *Intervention* considered is the utilisation of the Augmented Reality technology. The *Comparison* can be done with Virtual Reality technology for both training and operating environment, traditional training methods and remote maintenance support. The *Outcomes* of the application of these different methods, can be measured in terms of KPI related with the specific maintenance task. Common key performance indicators are time to complete the operation and the number of errors. The impact would affect the human performance in carrying out a maintenance task hence it is mainly economic and social dimensions. Finally, the *Context* includes industrial environment and “consumer environment” for both training and operating activities.

Finally, the SLR research questions have been defined as:

Q1: What is the state of the art of AR application in industrial maintenance for supporting human operators?

Q2: What are the potential future developments and implementation of AR in Maintenance?

2.2.3 Step 3 - Searching

The Searching step consists of browsing separately the databases identified at step 1 and listed in sec. 2.2.1 utilising the string: (“Augmented Reality”) AND (“Maintenance”). It has been selected based on the research questions and key concepts stated in sec. 2.2.2. Boolean operator “AND” is utilised to provide a more detailed first screening. The results of this searching step updated at the 13th of February 2017 is the collection of 723 documents.

Since this phase has been carried out for each database separately, the final number of 723 documents includes duplicates. More details are shown in Table 2.1.

Table 2.1 Outcome of the searching phase. The first column reports the databases utilised. These have been identified in Step 1. The second column reports the “search fields” where the search string has been applied. The third column reports the number of documents returned by the databases.

Database Name	*Search Fields*	*Documents returned*
Scopus	Title-Abs-Key	438
ScienceDirect	Title-Abs-Key	54
IEEE Explore	Metadata Only	165
Google Scholar	Title	66
	Sum	723

It is worth to mention that this step does not involve reading the titles or the abstracts of the documents found.

2.2.4 Step 4 - Assessing

The Assessing step aims to narrow down the hundreds of documents found in the searching phase to a final number of documents which are relevant for answering the research questions.

Inclusion and Exclusion criteria have been utilised to make the first screening of the documents:

Inclusion Criteria:

IC1) primary study that represents the use of AR in maintenance

IC2) primary study that represents the AR technology state of the art.

Exclusion Criteria:

EC1) Not in English.

EC2) Older than 1997.

EC3) Not engineering or computer science field.

EC4) Not related or applicable to industrial maintenance.

The selection of the criteria is made based on the author's experience and takes inspiration from other successful literature studies [9]–[11];

These criteria have been applied to the documents found in the four databases listed in sec. 2.2.1 separately and in three different phases: firstly, through the searching tools provided by each database selected have been used; secondly, through reviewing the title and the abstract and finally reviewing introduction and conclusion of the remaining documents. Only in the third phase, the documents derived from the four different databases have been collated.

The results of the application of the IC and EC are outlined in Figure 2.2

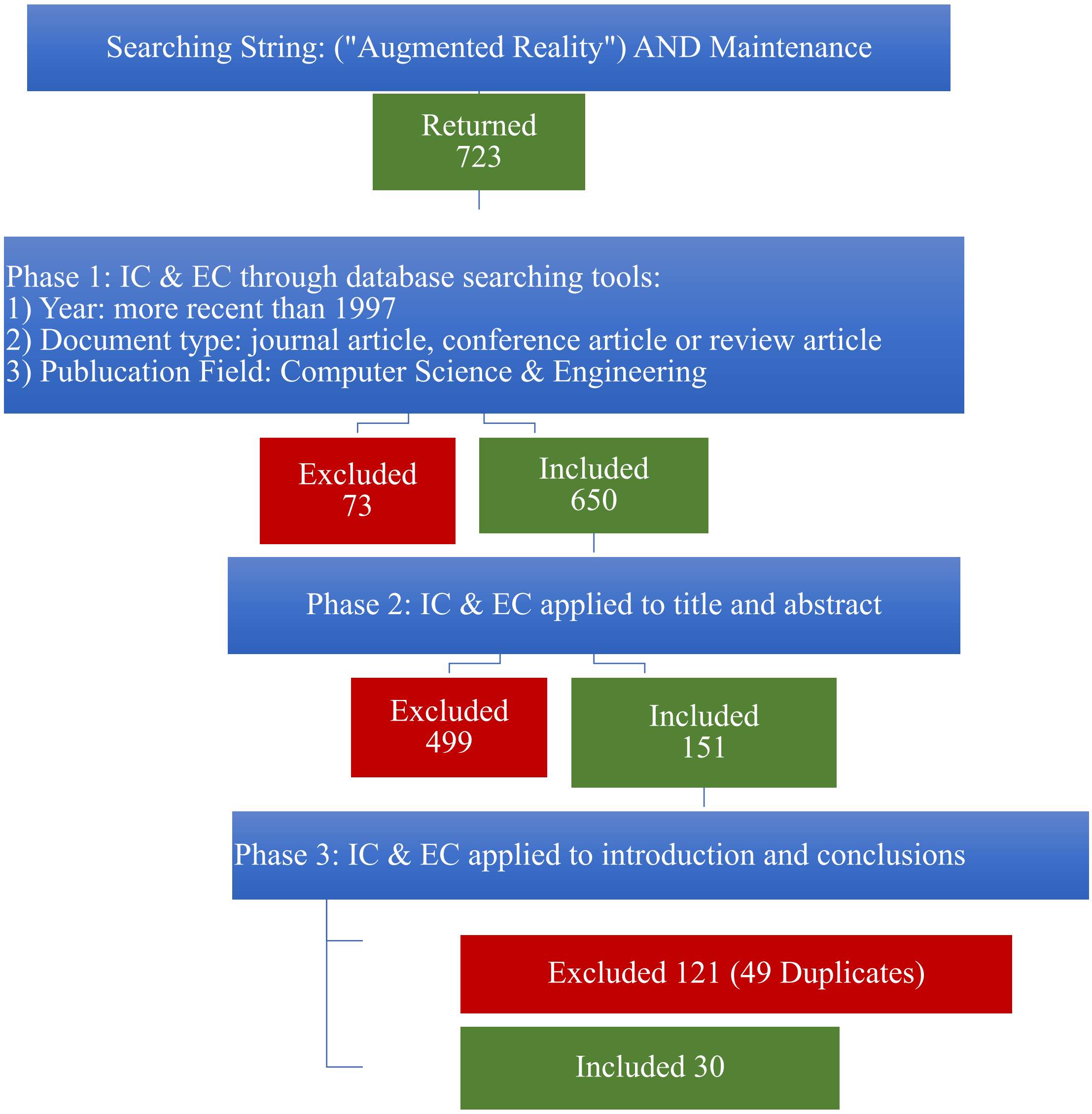


Figure 2.2. Selection Process of Primary studies. Starting from 723 documents collected in the searching step, the application of IC and EC narrowed the documents to 30 primary studies.

The result of the application of the Exclusion and Inclusion criteria is a list of 30 documents.

The next step has been to identify quality criteria in order to strengthen the extraction of quantitative and qualitative data for the synthesis and results analysis. Quality Criteria (QC) have been selected based on Santos [9].

Table 2.2. Quality Criteria selected for this project.

	Description
QC1	The document is clear
QC2	The methodology is well exposed and detailed
QC3	The technology and case studies are not obsolete
QC4	The study results are applicable to maintenance cases
QC5	Analytical results are provided

For each one of the 30 documents selected, a score from 0 to 5 has been calculated summing up the scores assigned for each QC. One point has been assigned for the full compliance with the QC; 0.5 points for the partial compliance. Table 2.3 reports the results of the application of the QC.

Table 2.3. Quality criteria applied to the 30 articles selected for this SLR. Each column reports the score assigned to one of the five quality criteria listed in Table 2.2.

Study ref.	QC1	QC2	QC3	QC4	QC5	Sum
[17]	1	1	1	1	1	5
[18]	1	1	1	1	1	5
[19]	1	1	1	1	1	5
[20]	1	1	1	1	1	5
[21]	1	1	1	1	1	5
[22]	1	1	1	1	1	5
[14]	1	1	1	1	1	5
[23]	1	1	1	1	1	5
[24]	1	1	1	1	1	5
[25]	1	0.5	1	1	1	4.5
[26]	1	0.5	1	1	1	4.5
[27]	1	1	1	0.5	1	4.5
[28]	1	1	0.5	1	1	4.5
[29]	1	1	0.5	1	1	4.5
[30]	1	0.5	1	1	1	4.5
[31]	1	1	1	1	0	4
[32]	1	1	0.5	1	0.5	4
[33]	1	1	0.5	1	0	3.5
[34]	1	0.5	1	0	1	3.5
[35]	1	0.5	1	1	0	3.5
[36]	1	1	0.5	1	0	3.5
[37]	1	0.5	1	1	0	3.5

Study ref.	QC1	QC2	QC3	QC4	QC5	Sum
[38]	1	0.5	1	1	0	3.5
[39]	0.5	1	1	0.5	0	3
[40]	1	0	1	1	0	3
[41]	1	1	0	1	0	3
[42]	0.5	0.5	1	0.5	0	2.5
[43]	1	0.5	0	1	0	2.5
[44]	0.5	0.5	0	1	0.5	2.5
[45]	1	0	1	0	0	2

Due to the subjectivity of the application of the quality criteria, these results are not used to exclude any study from this SLR. All the 30 articles identified provide valuable contribution to this SLR. Still, Table 2.3 was considered when referencing any study and reporting quantitative and qualitative results. Moreover Table 2.3 provides the reader with a tool to assess the quality of the qualitative results exposed in sec. 2.3. Finally, more considerations will be reported in the Conclusion section.

2.2.5 Step 5 - Synthetising and Analysing

In order to answer the research questions Q1 and Q2, the author analysed and synthetised the 30 articles identified through the systematic research.

It is relevant to clarify that only the 30 articles selected influenced the results of this SLR reported in sec. 2.3 (Figure 2.3, Figure 2.4, Figure 2.10, Figure 2.13, Figure 2.14, Figure 2.20 and Figure 2.22). In some cases, other relevant studies will still be utilised to describe the results and provide the reader with a better understanding of the topic.

In this step, it has been found necessary to build a table, which could correlate the documents in order to find trends and common features of the different studies. The author decided to build Table 2.4 which has as columns, the 30 articles and as rows, the main characteristic of an AR system: field of application, maintenance operation, hardware, development platform, tracking solution, interaction method and authoring solution. These main characteristics have been selected based on the papers and the author's experience in the field. For instance is not uncommon to find sections dedicated to the hardware, tracking and interaction methods across the AR studies [12], [46]. Moreover, usually the authors of AR studies mention the field of application and the development process of the AR system they are testing or developing, the maintenance operation considered and how the AR procedures have been built. The definition of each characteristic will be provided in the following sub-sections.

For each column in Table 2.4, comments have been saved for improving the quality of the data extraction.

Table 2.4. Example of data extraction from 30 articles selected for the SLR.

ARTICLE	REF 1	REF 2	REF 3	…
FIELD OF APPLICATION	Mechanical	Infrastructure Maintenance	Aircraft maintenance Inspections Diagnosis	
MAINTENANCE OPERATION	Dis/Assembly Maintenance Metal	Diagnostics	Inspection and diagnosis	
HARDWARE	Monocular Tablet HMD Mobile	HMD	Camera HMD (designed from sketches)	
DEVELOPMENT PLATFORM	Open GL	n/a	Open GL Rinocheros	
TRACKING SOLUTION	Model based Edges-point based 3D particle filter	GPS Image Recognition	Markerless Feature extraction SIFT SURF	
VISUALISATION	Animation	3D CAD static	Digital contents animations	
AUTHORING SOLUTION	Automated by CAD	Manual	Manual	

Due to different terminologies and the high fragmentation of devices and tools utilised by the authors of the paper analysed, an effort has been put to find more comprehensive categories for each characteristic recorded in the table. The categories are reported in the following subsections. The percentage of times these categories have been mentioned through the 30 articles of this SLR is reported in sec. 2.3.

2.2.5.1 Field of Application

By field of application is meant the industry and/or technological environment where the application of AR has been considered. The field of application characteristic of an AR system has been divided in six categories:

1. Aviation industry
2. Plant maintenance
3. Mechanical maintenance
4. Consumer technology
5. Nuclear industry
6. Remote applications

These categories have been selected as outcome of the compilation of Table 2.4 hence the analysis of the 30 articles selected in this SLR.

It is not unexpected that the fields application identified are not at the same level of detail and have different granularities. The selection process, in fact, is based on the analysis of the papers selected for the SLR and the statements collected throughout them and stored in le Table 2.4.

Another consideration could be that aircraft maintenance is a sub-category of mechanical maintenance, but it is not completely true. If we think about the requirements in terms of reliability and availability of a mechanical system embedded on a train, and one embedded on an aircraft, we could easily imagine they are different.

These categories have different requirements regarding the AR system and maintenance hence AR specifications are often justified by the field of application.

2.2.5.2 Maintenance Operation

The maintenance operation characteristic consists of the maintenance tasks that have been performed utilising AR. It has been divided in 4 main categories:

1. Dis/Assembly

2. Repair
3. Diagnosis
4. Training

Please notice these were the categories that were most mentioned among the filtered list of papers identified. In each paper that includes the development of an AR system, the author identified one or more maintenance operations that can be supported by the technology developed.

2.2.5.3 Hardware

The Hardware characteristic consists of the devices utilised in the AR system. It has been divided in 6 categories:

1. Head Mounted Display (HMD)
2. Hand Held Display (HHD)
3. Desktop PC
4. Projector
5. Haptic
6. Sensors

In some articles, the author utilises more than one of hardware or mentions the possibility of using a different hardware solution.

The category of HHD includes mobiles and tablets. Others includes mainly sensors utilised to capture data from the environment or other devices.

2.2.5.4 Development Platform

The Development platform characteristic consist of the software utilised to develop the AR system. It has been divided in 5 categories:

1. Mid/Low-level languages
2. Libraries of functions

3. SDK (Software Development Kit)
4. Game Engine
5. 3D modelling

These are the main categories of development tool utilised. “Mid/Low-level language” refers to a common term utilised in Computer Science for identifying a programming language which is close to the “machine language”. For instance, a high programming language is closer to the human language.

2.2.5.5 Tracking

The Tracking characteristic consists of the tracking technology or principle utilised in the AR system developed by the authors. It has been divided in 4 categories:

1. Model-based
2. Features-based
3. Marker-based
4. Others

2.2.5.6 Interaction method

The Interaction method characteristic consists of the way the AR systems mentioned by the authors of the 30 articles interact with the users. It has been divided in 4 categories:

1. Text
2. Audio
3. Static 2D/3D
4. Dynamic 2D/3D

Also, for these characteristics, some articles mention the possibility of using different interaction methods.

2.2.5.7 Authoring Solution

The authoring solution characteristic consists of the procedures and methods utilised by the authors to create the contents of their AR system. It has been divided in 4 categories:

1. Manual
2. By annotations
3. By "boxes"
4. Automated

For each one of the characteristics (1 to 7) of the AR systems, the author built a pie chart which shows the proportion of each category identified with respect to the others for each characteristic. These proportions have been calculated considering the number of times each one of the categories has been mentioned or considered throughout the nr. 30 papers. The charts are shown and discussed in sec. 2.3.

2.3 SLR Results and Discussion

This section reports the results of the SLR and the synthesis of the papers analysed. The aim of the SLR was to answer the research questions:

Q1: What is the current state of the art of AR applications in maintenance for supporting human operators?

Q2: What are the AR future developments in Maintenance?

These questions are answered separately in the following subsections.

2.3.1 Answer to Q1: the state of the art of AR applications in maintenance for supporting human operators.

In order to describe the state of the art of AR applications in maintenance, a summary of the 30 papers identified is provided and divided by the following characteristics: field of application, maintenance operation, hardware, development platform, tracking solution, interaction method and authoring solution.

2.3.1.1 Field of Application

By field of application of AR in maintenance is meant the industry or technological environment which have been mentioned and considered in the 30 studies selected by this SLR. Figure 2.3 reports the main fields identified.

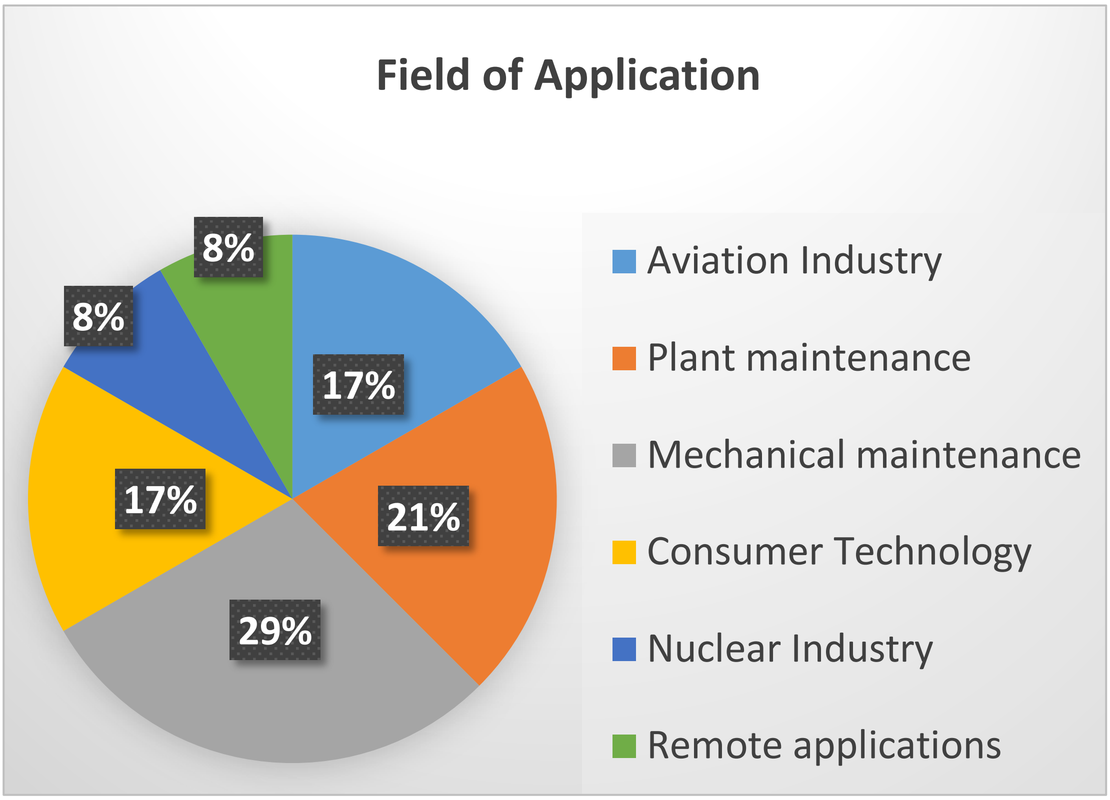


Figure 2.3. Field of application of AR for maintenance.

Figure 2.3 has been built utilising the methodology described in sec. 2.2.5. It is a representative figure of the field of application described and utilised as case studies throughout the 30 papers. This result align with Dini [47] who also found the aviation, industrial plant and automotive as the biggest field of interest for AR in maintenance. The biggest slice of the chart is taken by the mechanical field. It could be justified by the fact that it includes the automotive, train, military industry plus some general mechanical maintenance operations which have not been classified by the author. It is very common, in fact, that the AR application developed by a research team in an academic context, is tested utilising the assemblies and objects available in their own lab. Alvarez [19], in his research into marker-less object recognition and AR for supporting disassembly operations, validated his tool utilising five different mechanical assemblies, without specifying the field of application. In some cases, even if tested with a mock-up or in a laboratory, the author usually provides an insight of what the application has been thought for. For instance, Lakshmprabha [45] suggests to utilise his “camera&IMU based fast pose estimator” for enhancing training in a real working environment without providing any test on the specific case.

The field of application is usually justified based on the maintenance requirements.

Reading clockwise the pie-chart in Figure 2.3, the first field of application is the aviation industry. The strong interest of the aviation industry in AR technologies is justified by several motivations. De Crescenzio, mentioned that for improving air-transportation safety, there is a need of reducing human errors’ impact on maintenance operations [18]. Haritos [36] believed that traditional training methods are not applicable to the current technology available on aircrafts. The skills required for working with the current complex systems and avionics have to be supported by AR. Hincapie’ [40] reported that carrying out a complex assembly task following manuals or handbooks can lead the maintainer to frustration and a low quality performance. Moreover, it takes about 2000 hours to train an aviation maintenance inspector whose skills and knowledge are not easily transferable to another maintainer. More in general, there is a need for improving maintenance performance in aviation due to the constant need of ensuring safe operation at minimal cost [48].

Going clockwise, the second slice of the pie-chart in Figure 2.3, reports the percentage of applications in plant maintenance mentioned or shown across the 30 articles. This field includes the maintenance of facilities, buildings or infrastructure which provides a living or working environment.

It is evident that, since facilities are designed and built to last for many years, the longest period of its lifecycle will be the Operations and Maintenance (O&M [17]. Its cost can be up to 85% of the total lifecycle cost.

Behzadan [42] believes AR could provide a solution to damage prevention and maintenance for underground infrastructure. The example considered in his research is an excavation operation which has a “high risk of inadvertently damaging the existing subsurface utilities”, mainly causing a financial loss, less commonly accidental deaths. Goose [41], states that “service and maintenance are by necessity mobile activities”, hence a mobile support is required. Moreover, his intent was to empower the industrial maintenance through allowing any maintenance technician to carry out the plant maintenance. Particularly relevant for the facility maintenance field, seems to be the localisation of the target to be maintained. Both Neges and Lee [23], [48] considered it necessary in order to improve O&M efficiency. The first one based his research on natural markers for indoor navigation. The latter one developed an AR application which integrates the facility management data available from the Computerised Maintenance Management System (CMMS) and the Building Automation System (BAS) . In his tests, he saved on average 51% of the time to locate the target.

The “mechanical field” is the third highest area of application, as highlighted in Figure 3. It includes the maintenance activities related with mechanical components in different sectors: automotive, train and military. It is worth to mention that, for the automotive industry, repair and maintenance accounts for 40% of the total lifetime costs of vehicle ownership [49].

Fiorentino [22] believes that “maintenance process is nowadays an important aspect of competitiveness and profitability”. In his study, he applied AR to a complex maintenance operation on a motorbike engine. His results show improvements in terms of both time (up to 79%) and reduced error rate (up to 92.4%).

Didier [33], on his side, aimed to resolve two issues of traditional maintenance related with the train industry:

1. transform manuals into electronic multimedia.
2. provide a tool for assisting and shortening the training of new technicians.

The fact that hard manuals delay maintenance operations is reported also in other studies [e.g. 23; 45]. Henderson [28] states that by utilising HMD the operator would not need to read the paper manual hence his/her concentration could be focused on the task. Reinhart [50] reports that AR could “reduce eye and head movements improving spatial perception and thus increase productivity”. Yuan [51] believed that alternating the attention between the object to maintain and the instructions, would consume valuable time. These concepts are valid also for the other fields of applications.

Moving now to the next slice of the pie-chart in Figure 2.3, we can see that consumer technology has been mentioned 17% of the time across the 30 articles of this SLR. Many examples provided in literature demonstrate the application of maintenance task on “consumer technology” such as printers and notebooks. The papers referenced in this SLR, do not state the necessity of using AR for maintaining consumer technology. It is the author’s belief that AR applied to consumer technology mostly aims to demonstrate the capabilities of the AR systems, often reproducible in other maintenance fields. Havard [38] demonstrated how AR can help in disassembly operations utilising the task of dismounting a pc blower. Sanna [25] aimed to gather data of non-expert maintainers using AR. For this reason, he considered a maintenance procedure of a notebook. His results show a reduction of both errors and time using AR-based instructions rather than paper-based instructions. Finally Lamberti [31], shows the capabilities of AR applying it on a notebook and printer maintenance operations even though he describes the automotive and aviation maintenance industry as the one needing for cost maintenance reductions. His research partners predicted a reduction of about 40% in travels and 30% in cost for maintenance operations.

Continuing the clockwise reading on Figure 2.3, 8% of the studies mentioned nuclear power plants as an interesting field of application for AR in maintenance. Similarly, to the relation between the aviation and the automotive field, nuclear facilities are more complex and require more reliability compared with other industrial facilities. Nuclear power plants’ maintenance is expensive and complex

[43], hence lot of procedural documentation is produced. Minimising their down time and safety is essential [24]. These concepts have been shown in the past by Nakagawa [44] who predicted the increasing challenge of maintenance for the nuclear industry. He stated that due to the rigid maintenance schedule, even well-experienced crews could incur errors resulting in time and cost growth. Martinez [52] claims that, not only because of their complexity, but also because of the presence of radioactive environments, nuclear power plants maintenance need to be optimised. In his case study, he faced the accessibility of the LHC (Large Hadron Collider) collimators which has changed after the design due to the installation of new equipment.

Finally, in the last slice of Figure 2.3, we find the applications that mention the utilisation of AR for remote maintenance. By remote maintenance is meant the collaboration between an expert and a maintainer that are in two physically different locations. Authors sometimes refer to it as “collaborative maintenance” or “remote assistance”. The application of AR for enhancing remote maintenance is mentioned in several papers [13], [21], [25], [30], [31], [38], [39], [41], [53]. Wang [39] reported that traditional remote assistance made “on-the-phone” cannot satisfy current technology complexity. He also mentioned that, even if VR can improve maintenance training while AR could provide a solution for transferring information from expert to technician real-time. Havard [38] reports from Bottecchia [54] that AR for collaborative maintenance is 10% faster than phone assistance. AR for remote maintenance is particularly relevant for machine tool makers. Lamberti [31] states that machine tool makers, represented in the EASE-R^3 project, find expansive providing assistance to their customers. Moreover, since every machine is different from the other, custom maintenance procedures are required. Improving the remote assistance could lead to both increasing customer satisfaction and reduce maintenance costs. Also the automotive industry is sensible to the remote collaboration topic [55]. Nowadays, in-vehicle sensors provide the capabilities for accessing diagnosis and maintenance information remotely [56]. Car manufacturers, workshops, road assistance services and the customer could all benefit from a new collaborating system. It is worth to mention that remote AR finds also other applications in the life-cycle of a product. Wang [57], for instance, proposes a collaborative design system which integrates AR and telepresence technologies. Liverani [53] believed that giving to operators and engineers the possibility to work on the same product, at the same time, even if located remotely, could not only shorten the time-to-market, but also improve the manufacturing quality.

The main fields of application of AR in maintenance have been explained. In general, the complexity of the technology and the constant need for improvements in terms of time, errors, safety and costs are the drivers for justifying the utilisation of AR. Each field of application seems to have its specific needs and reasons for investing in AR.

2.3.1.2 Maintenance operations

The second figure, relevant for understanding the state of the art of AR in maintenance, is shown Figure 2.4 .It shows the percentages of maintenance operations mentioned through the 30 articles analysed. Even in this case, some authors, developed demonstrators based on one maintenance operation and then stated their replicability for other purposes.

It can be noticed that the smallest slice is ‘training’. It can be justified by the fact that, when talking about AR, the aim is to avoid or reduce training and propose a solution which affects directly the maintenance operation [21;24;37]. Through the use of AR, maintainers could have the “immediate capability to accomplish the task” on the job [58].

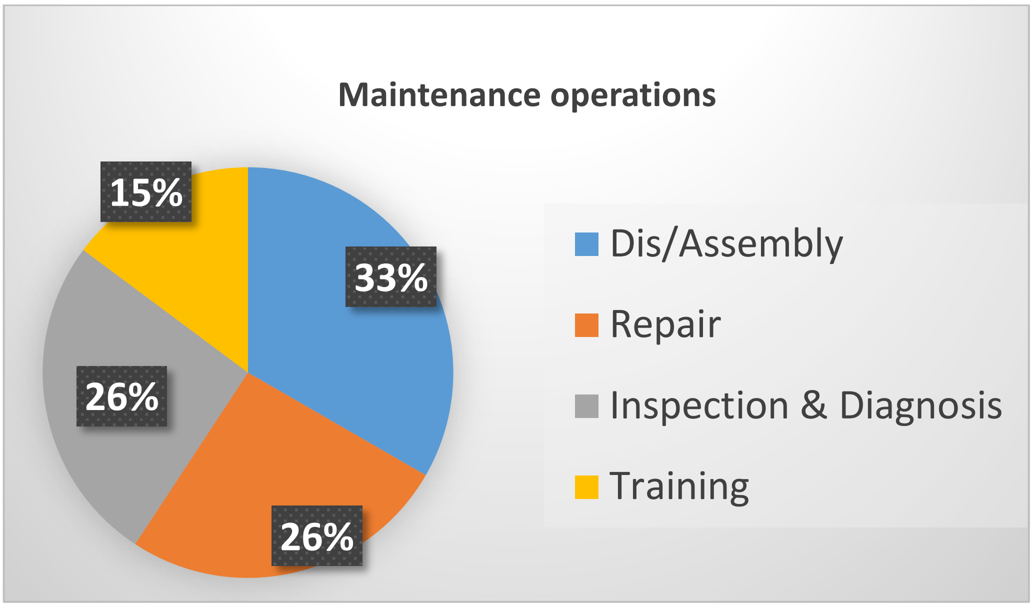
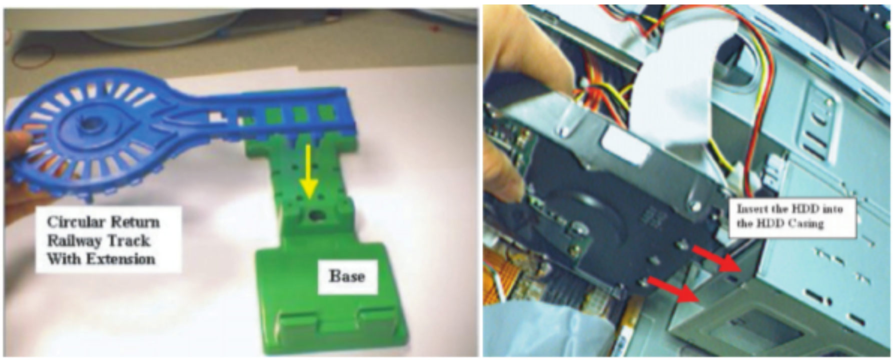


Figure 2.4. Maintenance operations mentioned across the 30 articles identified in this SLR.

Starting from the top right slice of the Maintenance operations pie-chart, assembly and disassembly seems to be the most common maintenance task taken in account across the 30 articles.

Already in 1997 Azuma [15] stated that superimposing 3-D animated drawing could ease the assembly processes compared to traditional user manuals. More recently Westerfield [6] considered AR as the "ideal tool for situations which require objects manipulation such as manual assembly". Yuan [51] described the assembly domain as one of the most promising applications of AR.

Few examples from literature are reported below, in order to get a better understanding of the utilisation of AR for supporting assembly procedures.



(a) (b)

Figure 2.5. Example of assembly instruction on a train toy (a), computer (b), Yuan [51]. Virtual arrows and text are overlaid on the real environment to provide guidance with the assembly procedure.

Figure 5 demonstrates a very simple AR approach which overlays virtual arrows and text to the real environment [46]. It has to be mentioned that Yuan focused his research on the development of a virtual interactive tool for supporting AR, and not on the user experience.

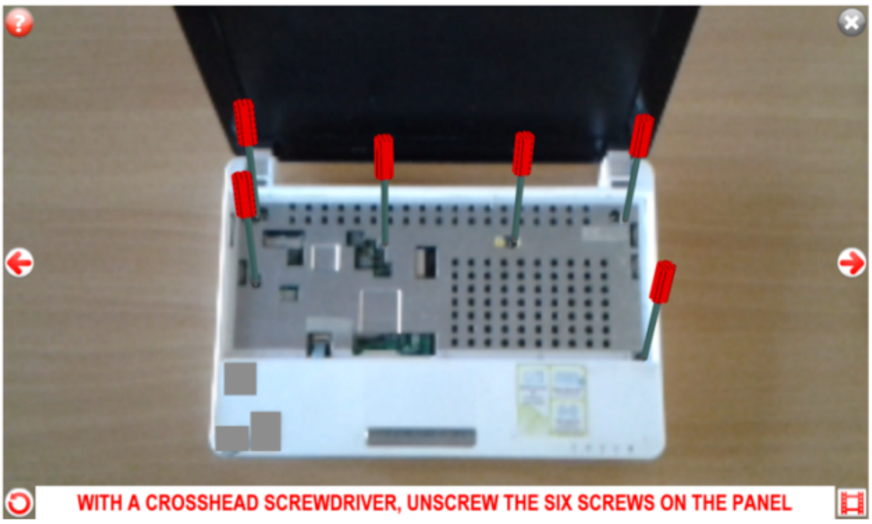
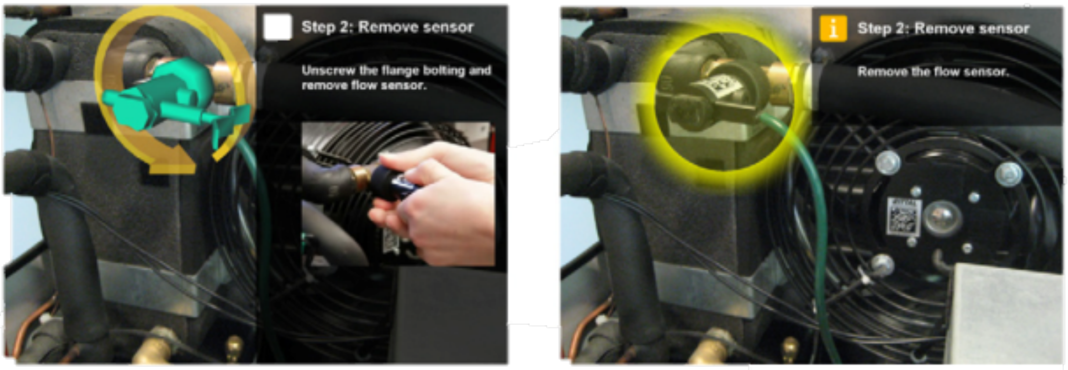


Figure 2.6. Step by Step assembly procedure by Sanna [25]. Text description of the task is provided on the bottom. Right and left arrows to go forward and backward through the procedure steps.

The example in Figure 2.6 is taken from Sanna [25]. He used HHD to carry out maintenance tasks on consumer devices. He decided to show the description of the task in the bottom of the display and provide few buttons to navigate through the procedure. Virtual animations are overplayed on the real environment at each step.



(a) (b)

Figure 2.7. Two types of visualisation for the same step in a disassembly procedure. In , Figure 2.7a "strong guidance", in Figure 2.7b "soft guidance", Webel [30].

The third example (Figure 2.7) provided by Webel [30], shows an effort in providing different levels of instructions. In his research, he proposed two level of guidance: a strong one which support the user in every single step, and a soft one which gives more top-level information and is thought for more experienced users.

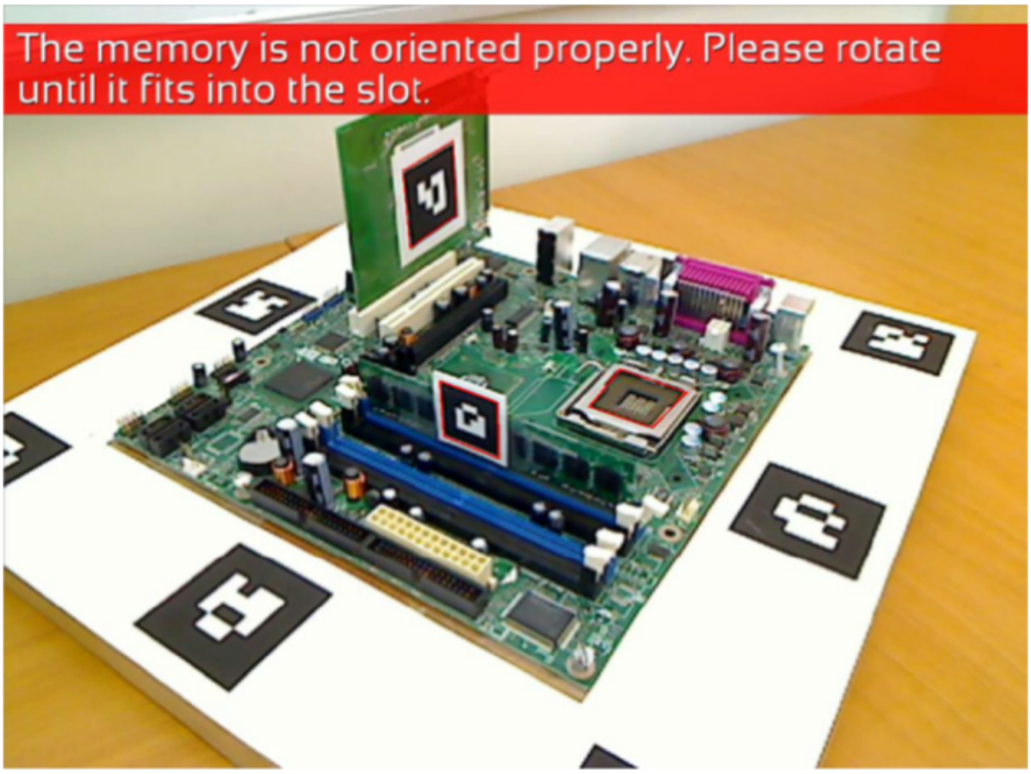


Figure 2.8. Example of negative feedback message in performing assembly through AR by Westerfield [6]. The recognition and tracking of the components is made by mean of markers.

Westerfield [6] incorporated in the AR procedure the ability to provide a real-time feedback of the operation (Figure 2.8). Through the position and orientation of the components, he is able to show warning messages to correct the assembly procedure.

Finally, a slightly different approach has been proposed by Wang [59]. He developed an AR application for simulating assembly procedure during the early design phase of components. In his study, he also estimates the forces involved in the assembly considering the stiffness, shapes and contacting surfaces of both the real component and the virtual prototype. The forces calculated real-time and overlaid on the real scene.

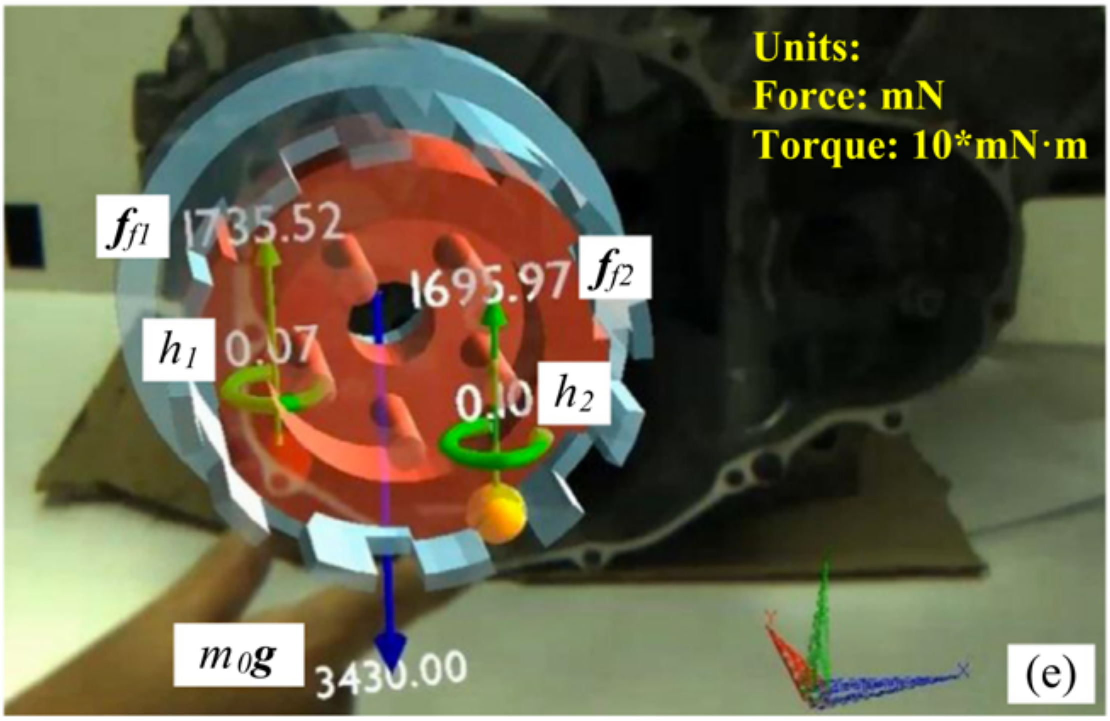


Figure 2.9. Assembly planning through AR. The virtual component is overlaid on the real component. Forces are shown as arrows. Their magnitude is reported numerically. Adapted from Wang [59].

The examples provided aim to demonstrate that, even for what might seem to be a straight forward task such as an assembly procedure, there is several types of information that might be interesting for the operator. An effort is required to gather the requirements of every assembly procedure in order to provide the best AR solution.

The other three slices of the chart in Figure 2.4 shows the percentage of times that repair (26%), inspection and diagnosis (26%) and training (15%) operations have been mentioned through the 30 articles analysed.

Even though these are three different kinds of maintenance operations, the AR applications developed by the authors of the 30 articles, always involve dis/assembly procedures.

- By repair operations is meant the actions aimed at restoring the functional properties of a device [37]. Repair operations commonly involve the regeneration or replacement of the failing component of the device.

- By inspections and diagnosis are meant maintenance task aiming to respectively assess the current status of the product and analyse the causality of deterioration and functional degradation [60]. Nowadays complex systems are embedded with sensor which provide the information about the functionalities and an initial diagnosis. This information is usually accessible on a dedicated PC. AR could enhance this process by displaying the results of the diagnosis closer to the object to be maintained [61].
- By training is meant the process that aims to transfer maintenance skills to technicians [30]. Depending on the industry, this process might be done on the job or offline. In the construction industry, hands-on training is well-accepted [62]. In this field, Wang utilised AR for complementing human associative information processing and memory. He overlaid technical information on real construction vehicles such as loaders, excavators and bulldozers to help the operator carrying out the construction operation. As stated by Neumann [63], in fact, AR demonstrated to be an efficient way for retrieving information from memory. This shows that AR training could offer the advantages of a VR training adding the value of performing it in the real environment rather than in an immersive one [64].

Figure 2.3 and Figure 2.4 give an initial overview of what is the state of the art of AR in maintenance. The main fields of application and operations performed have been described. In order to get a deeper understanding of the current AR technology utilised, more technical information is required. In the development process of an AR application for maintenance, in fact, the developer usually has to make different choices. He/she has to select what device he/she wants to use to overlay the digital contents to the real world, what development platform he/she will be using, how the user interface will look like, what will be the tracking technology be and how the contents will be built. The following subsections will show an overview of what are the most common devices, development platform and solutions utilised by the authors throughout the 30 papers analysed.

2.3.1.3 Hardware

This subsection provides an overview of the most common devices utilised in the development of an AR application in maintenance.

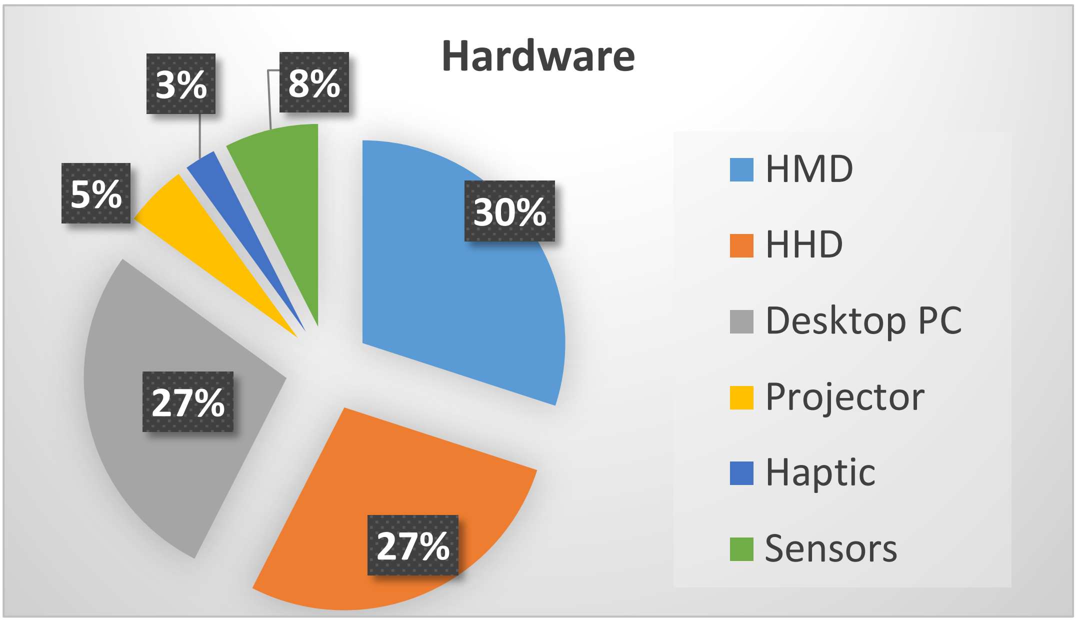


Figure 2.10 Hardware mentioned throughout the 30 articles analysed in this SLR.

Figure 2.10 is representative of the main devices mentioned and utilised in the 30 articles selected and analysed for this SLR. The utilisation of one device rather than another is often justified by the purpose of the AR application developed by the author. The progress of the technology needs to also be considered in analysing this chart.

Starting from the top and reading clockwise, the first slice of the pie-chart reports the percentage of times HMDs have been mentioned in the articles. Since this SLR considers only articles more recent than 1997, the several attempts to develop HMD that were made in the early 90s [15] are not considered. The devices mentioned in the 30 articles of this SLR are usually commercial devices available on the market. Compared to the past, current technology is closer to the requirements in terms of weight and resolution asked by industrial customers, but not limited to this. Two types of HMD can be identified: see-through HMD and video display HMD [8; 9]. The technology of the first one is based on semi-transparent mirrors which allow the operator to “see-through” and, at the same time are able to reflect computer generated images into the user’s eyes. Pupil forming and non-pupil forming are the two main optical architectures utilised in this kind of device. The latter is widely utilised by commercial HMDs. Kress [65] in his review of head-mounted displays, provides a detailed explanation of the optical approaches (for both pupil and non-pupil forming) concluding that there is “not yet any standard optical combiner architecture which prevail since there is a trade-off between having a large eye-box, a large Field Of View (FOV) , allowing relocation of the image, etc.…”.

The video display HMD, on the other hand, captures the real world, overlays the computer-generated information and shows the AR world through a small display placed in front of the eye [66]. Video display HMD have a higher latency (time gap between what is happening on the real world and what is perceived by the eye) compared to the see-through HMD due to the bigger amount of information that has to be processed.

The main technical challenges for both types of HMD include latency of the system, resolution, FOV, scene distortion, eye-point matching, ergonomics and costs [10; 14; 26; 30; 59; 62].

The main advantages of using HMDs are the portability and the user experience in having the computer-generated information overlaying the real world straight in front of the eye [8; 46; 63].

The second slice of the chart in Figure 2.10 reports the percentage of times HHDs have been mentioned in the articles. HHD includes mainly consumer devices such as mobiles and tablets. Their cost, capabilities and portability make them two very promising platforms for AR [69]. Kim [70] believes AR applications on smartphones have the potential to substitute paper-instructions in consumer cars. On the other side, the dimension of their screen and their need to be supported (hand held or by a support designed ad-hoc), make them not suitable for all maintenance jobs [29].

The third slice of the pie-chart includes the applications that utilise Desktop PCs. Their relatively high utilisation across the 30 articles is justified by the fact that this type of device is utilised for different reasons: remote maintenance applications (on the expert side), for static maintenance activities (work bench), for developing a prototype, for modifying the AR procedures. When utilised for carrying out the maintenance task, such AR systems usually include the utilisation of one or more cameras for capturing the environment and the operations.

The hardware described until now have their advantages and drawbacks.

Only a small percentage of the articles explored the use of other visualisation systems. For instance Fiorentino [22] made an effort in demonstrating the capability of improving maintenance performance in a workshop simulated environment through the use of a large screen. The system also included three cameras: one pointing at the object, one at the tooling and one placed on the body of the operator. When the projection is made on the physical object, the system is called Spatial AR [71].

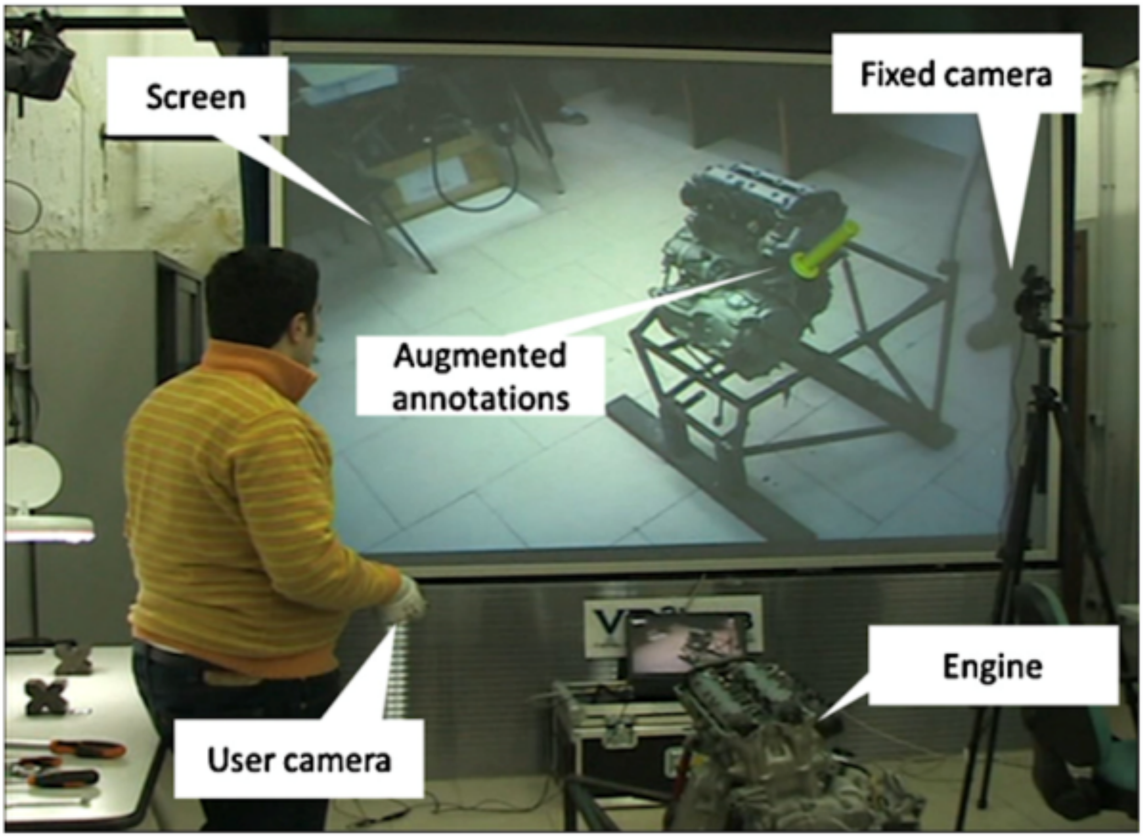


Figure 2.11. Interactive AR instructions on a large screen. A motorbike engine on the bottom is captured by the user camera end projected on the screen. Fixed cameras enhance the tracking. Fiorentino [22].

The last two slices of Figure 2.10 report the times haptic devices and other sensors have been mentioned through the 30 articles. These devices aim to gather more data from the operation and the environment. Haption devices have been considered in AR for enhancing the interaction with the virtual objects [46]. Webel [30], utilised a vibrotactile bracelet for assisting in performing the task. The operator was driven by the vibrations of the bracelet in rotating the hand in the correct direction (Figure 2.12).

Figure 2.12. Example from Webel [30] of the utilisation of vibrotactile bracelet (on the right arm) for supporting maintenance task. Tabled with external camera pointing and the object to maintain. The AR animation is displayed on the tablet screen.

The utilisation of other sensors depends on the specific application.

2.3.1.4 Development platforms

In the process of developing an AR system, the developer has to choose one or more platforms to utilise for the development.

below, in Figure 2.13, the pie-chart shows the percentage of times that different development platforms of programming languages have been mentioned across the 30 articles of this SLR.

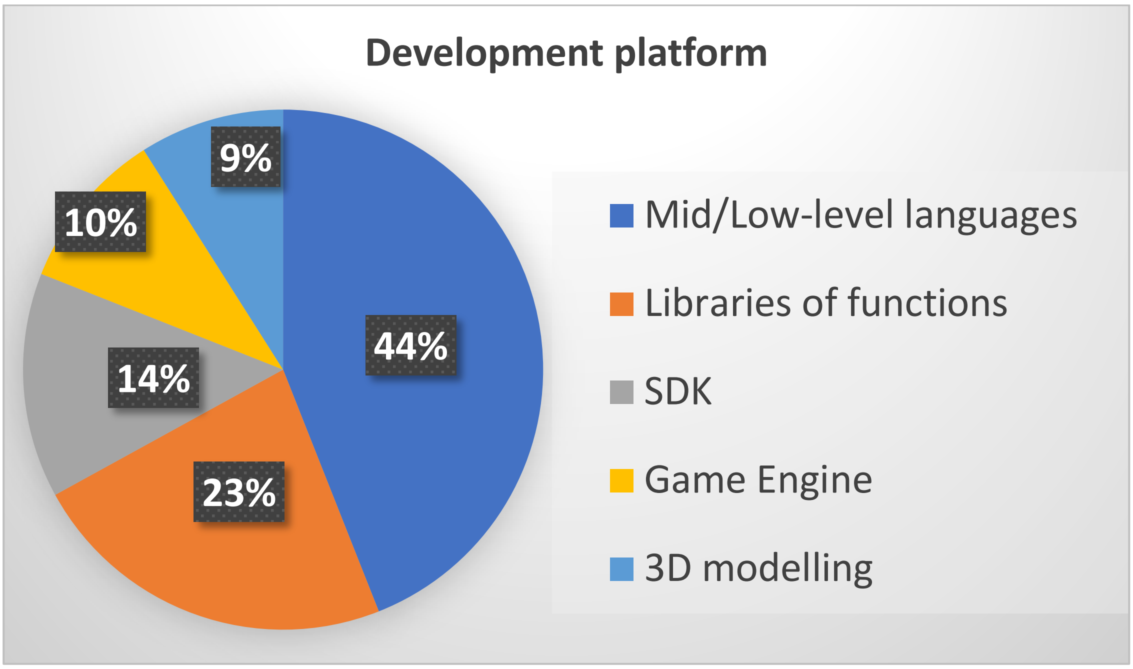


Figure 2.13. Development platform mentioned throughout the 30 articles of this SLR.

In Figure 2.13, it is evident that mid/low programming languages have been widely used to develop AR applications in maintenance. By mid/low level programming language, it is meant a programming language, which is closer to human language rather than the machine one. The authors of the 30 articles, not always specify the development process hence the most utilised programming languages have not been listed. Not considering the 30 articles, the most commonly utilised are: c++, c#, java, HTML, CSS, Python, Visual Basic and PHP. Widely used are also libraries of functions such as OpenCV (Open Source Computer Vision), OpenGL (for rendering 2D and 3D graphics) and MatLab libraries. Both the solutions mentioned in the first two slices of the chart allow developing an application from scratches hence ensuring high flexibility. The drawback is that highly skilled people are required for developing such systems.

The utilisation of SDK was mentioned only 14% of the time across the 30 articles. SDKs are becoming more common lately since they usually come along with new devices on the market (e.g. HMD, HHD). Often, in order to develop an AR application, SDKs are not enough and have to be included in a wider software developed using mid/low level programming language or game engine.

Game Engines have been mentioned 10% of the time. The most common game engines utilised for developing AR applications are Unity3D and Unreal. These are user friendly platforms which allow building applications with a minimum knowledge of programming languages. Still, skilled AR people are required to utilise them.

Finally, other development platforms have been mentioned through the articles. In creating the contents of an AR application, 3D modelling platforms are utilised such as Rhinoceros, SolidWorks, Catia and 3dsMAX.

2.3.1.5 Visualisation

Figure 2.14 reports the visualisation methods utilised by the authors to overlay computer-generated information on the real environment. The devices through which the interaction user-AR is exploited are reported in Figure 2.10.

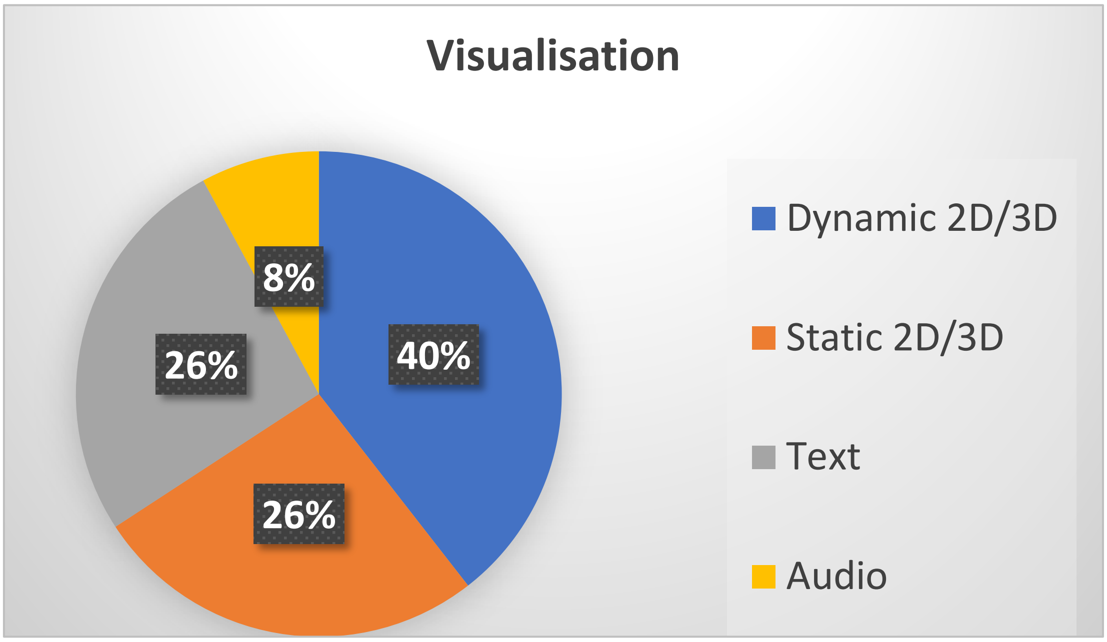
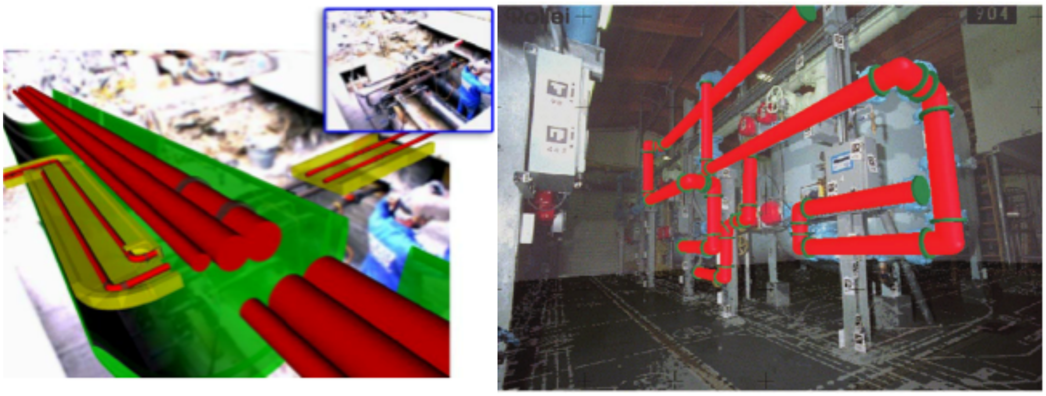


Figure 2.14. Visualisation approaches mentioned throughout the 30 articles analysed in this SLR.

The most common method utilised and mentioned is through dynamic 2D/3D. It includes 2D and 3D animations which give more vivid instructions to technicians compared to other methods [39]. These animations virtually show the task that has to be performed by the operator providing hints to perform it correctly, especially to unskilled operators [18]. These instructions are considered more effective than paper-based instructions [22]. An example of this visualisation system is provided in Figure 2.15.

Figure 2.15. Example of animation related with aviation industry from De Crescenzio [18].

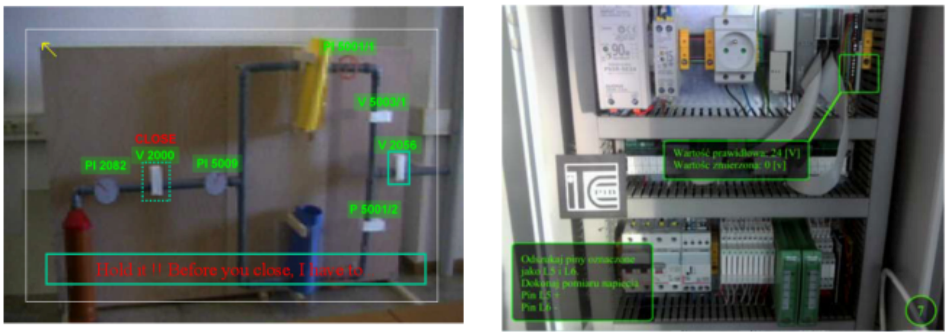
Another effective way of overlaying information is through 2D/3D static models. In some cases, in fact, there might be no need to provide an animation of a maintenance task, but only a static model with information relevant to perform inspections or other operations. Schall [67], for instance, proposed to superimpose a 3D model of underground infrastructure on a construction site Figure 2.16a. Navab [64] shows CyliCon as a promising application for visualising 3D models in industrial environments Figure 2.16b.



(a) (b)

Figure 2.16. Example of 3D static superimposition on the real environment for underground infrastructure (a) adapted from Schall [67] and for industrial environments (b) adapted from Navab [64].

Another less intrusive way to provide information related to a machinery or assembly task is through text. Overlaying text information does not obstruct the field of view and text contents are easier to create and update. Text information might be more suitable for improving maintenance performance of already skilled operators. Figure 2.17 provides two examples from literature.



(a) (b)

Figure 2.17. (a) View though HMD of a helium flushing system (mock-up) from Klinker [43].(b) View of an electrical cabinet though HHD or HMD adapted from Wojcicki [37].

A small percentage of the studies mentioned the utilisation of audio guidance for supporting maintenance. Please note that this percentage does not include the studies which mentioned the utilisation of voice recognition systems to navigate in the AR application.

In general, it is worth mentioning that the contents and context requirements have to be considered in order to develop the best AR solution. Engelke [35], believes that the operators should be allowed to visualise the instructions in the form of which is more suitable to them. In his research, he introduced the capability of switching from one visualisation method to another (Figure 2.18).

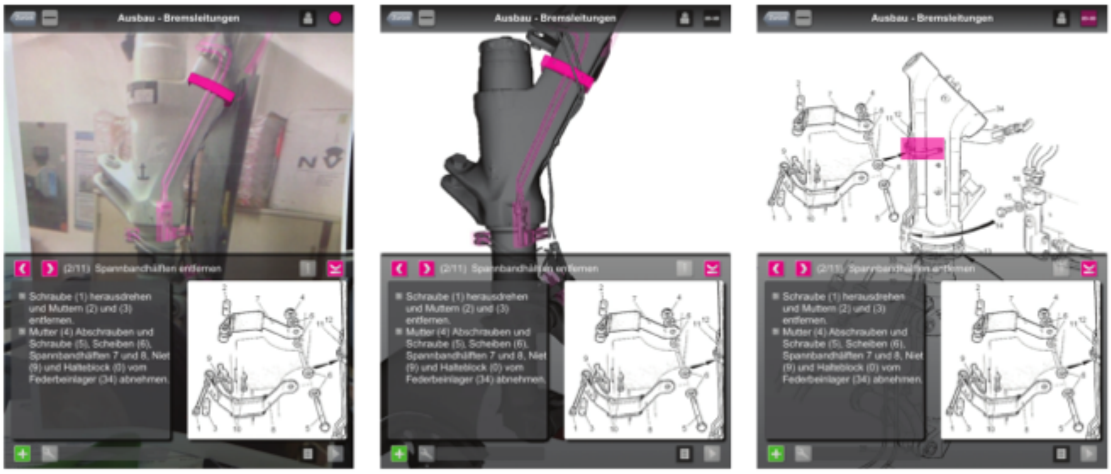


Figure 2.18. Three visualisation method proposed by Engelke [35].

On the left, the system to be maintained is overlaid on to the real environment. In the centre the full CAD model of the assembly is shown. On the right AR highlights the area of interest for the maintenance task on the 2D drawing. All of them provide the manual instructions on the bottom.

Having described the hardware, development platforms and visualisation methods commonly used for AR applications, the next paragraphs will describe the tracking techniques solutions and the authoring solutions.

2.3.1.6 Tracking

Tracking has been defined by Siltanen [72] as the “heart” of AR systems: it calculates the relative pose of the camera in real time. By pose is meant the position and orientation (6 DOF) of an object. Ong [2], stated that an accurate tracking, which locates the users and their movements in reference to their surroundings, is a crucial requirement for an AR application. Zhou [12] listed tracking as one of the main AR research topics.

Tracking techniques can be visual-based and sensor-based. We refer to hybrid-tracking when both the techniques are utilised at the same time [73]. Visual-based tracking techniques can be divided in two categories: “a priori” methods and “had-oc” methods. The first one implies that the AR system has an “a priori” knowledge about the object that will be tracked. They can be divided in: model-based, feature-based and marker-based. It means that the information available a-priori are respectively: a model, a feature-map and a marker. The information can be created utilising an “had-oc” visual tracking method hence providing the initialisation of the a-priori visual tracking method [72]. Figure 2.19 schematically reports the tracking techniques described.

It is relevant to mention the difference between recognition and tracking. The first one does not rely on any previous information provided by the camera and aims to estimate the camera pose. Recognition is made at the initialisation of the AR system and whenever there is a tracking failure. The latter aims to track the camera pose based on the previous frame provided by the camera [19].

Across the 30 articles analysed in this SLR, 90% made use of “a-priori” vision-based tracking techniques (Figure 2.20).

Vision based methods are generally preferred due to the wide diffusion of RGB cameras across the different hardware utilised for AR (Figure 2.10). The information required to run the “a-priori” tracking is usually developed by the authors for the purpose of their project.

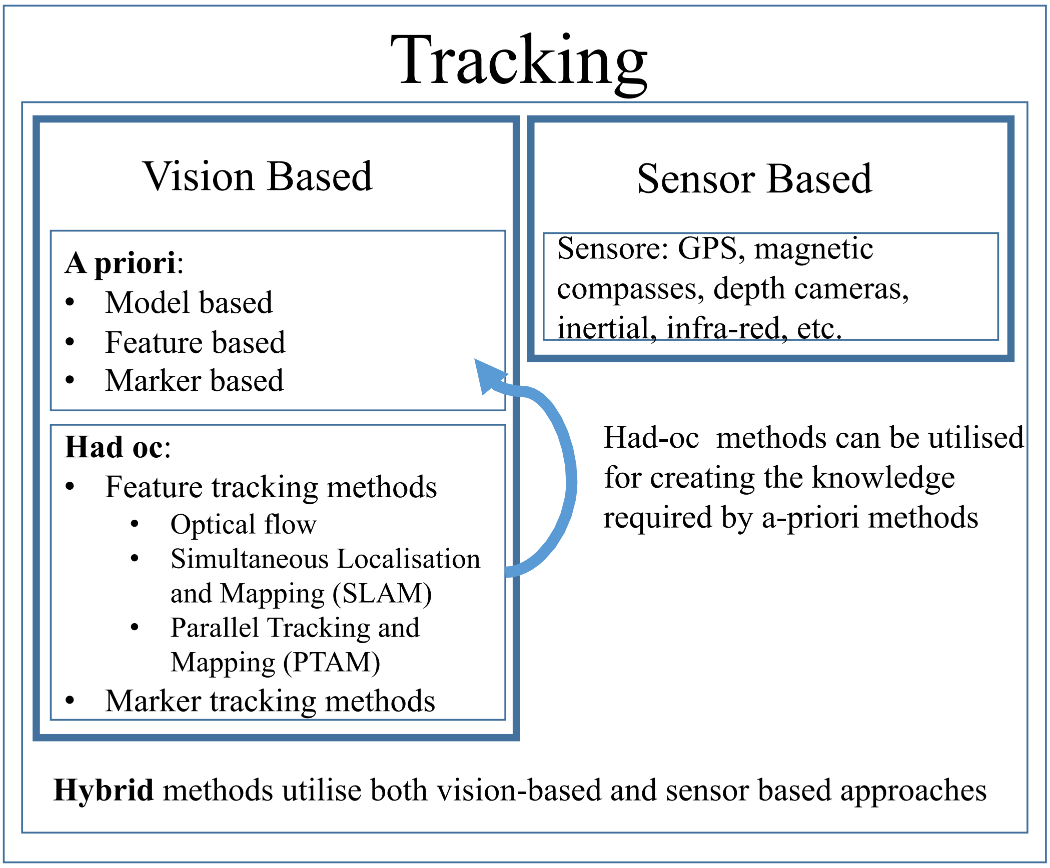


Figure 2.19, Scheme of the tracking approaches extracted from Siltanen [72] , Yu [73] and Hincapie [40].

Sanna [25] utilised both a-priori model based and a-priori feature based ("by images"). The first one is considered more robust and reliable since it is independent from environmental conditions (lighting, materials, etc.). The limitation resides on the availability of the CAD models. Same considerations are made by Platonov [32] who also stated that CAD based tracking solves issues such as partial occlusions and rapid motion.

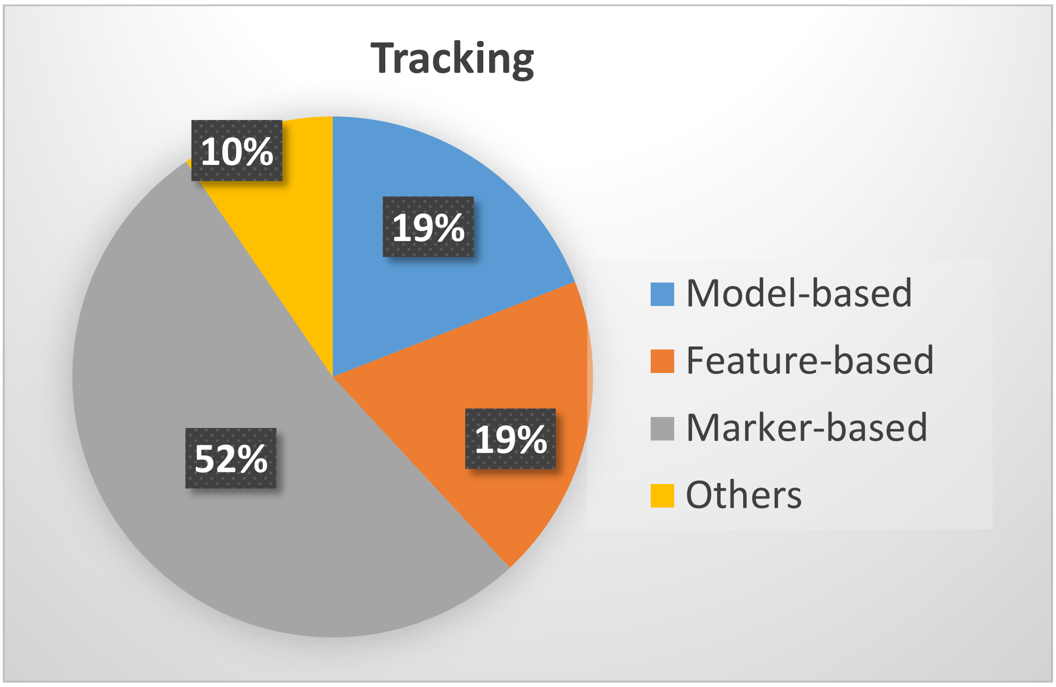


Figure 2.20. Tracking techniques mentioned throughout the 30 articles of this SLR.

The marker-based approach, which is considered robust and accurate, might not be so in an industrial environment [22]. Marker based tracking consists of placing physical markers on the object that has to be maintained. The configuration of markers has to be properly designed. These markers, their position and orientation on the real object to be maintained, are registered a-priori on the AR system. In this way, recognising the marker means recognising the object. Marker based tracking limitation relies on the visibility of the marker which might not always be in the frame of the camera. In an industrial environment, for instance, there are a lot of objects which could occlude the vision of the marker (people, tools, machineries, etc.). This would cause the tracking failure of the AR system [53]. Moreover, the markers have to be maintained (clean and not damaged) in order to perform properly. For these reasons, marker-based approach is not suitable for harsh industrial environments [21].

The aviation industry also considers unacceptable the application of markers on the real environment [18]. For this reason both De Crescenzio [18] and Koch [17], for instance, proposed the utilisation of natural markers. These are fiducial images which already exist in the environment, hence there would be no need for placing markers in the facility or on the aircraft. Some examples of natural markers are shown in Figure 2.21.

Figure 2.21. Examples of Natural Markers adapted from Koch [17]

In construction, the hybrid tracking technology is well appreciated. In this field AR systems usually take advantage of GPS for improving the accuracy of the model-based or feature-based tracking [42]. This approach belongs to the 10% of other tracking methods shown in Figure 2.20.

2.3.1.7 Authoring Solutions

The last chart in Figure 2.22 reports the percentages of time that different authoring solutions have been mentioned across the 30 articles of this SLR. By authoring is meant the process of creating digital contents for augmenting the reality [20]. The most common contents are shown in Figure 2.14. Santos [74] mentioned “authoring tools” as one of the AR contents-related issues, together with instruction design and content management tools. Langlotz [75] stated that authoring tools as the AR solution to the widely known contents problem. Bae [76] lists it as one of the two key components of mobile AR along with pose estimation.

In the pie-chart in Figure 2.22, it is possible to see four categories. These have been identified applying the methodology described in sec. 2.2.5.

The first one includes manual authoring processes. This means that the contents are manually generated. It includes not only the creation of the 3D/2D dynamic/static models, but also their implementation in the AR system (location, orientation, etc.). Manual authoring is expansive due to the amount of time and skills required in performing it. The professional skills involved are: programming, modelling and animation [20].

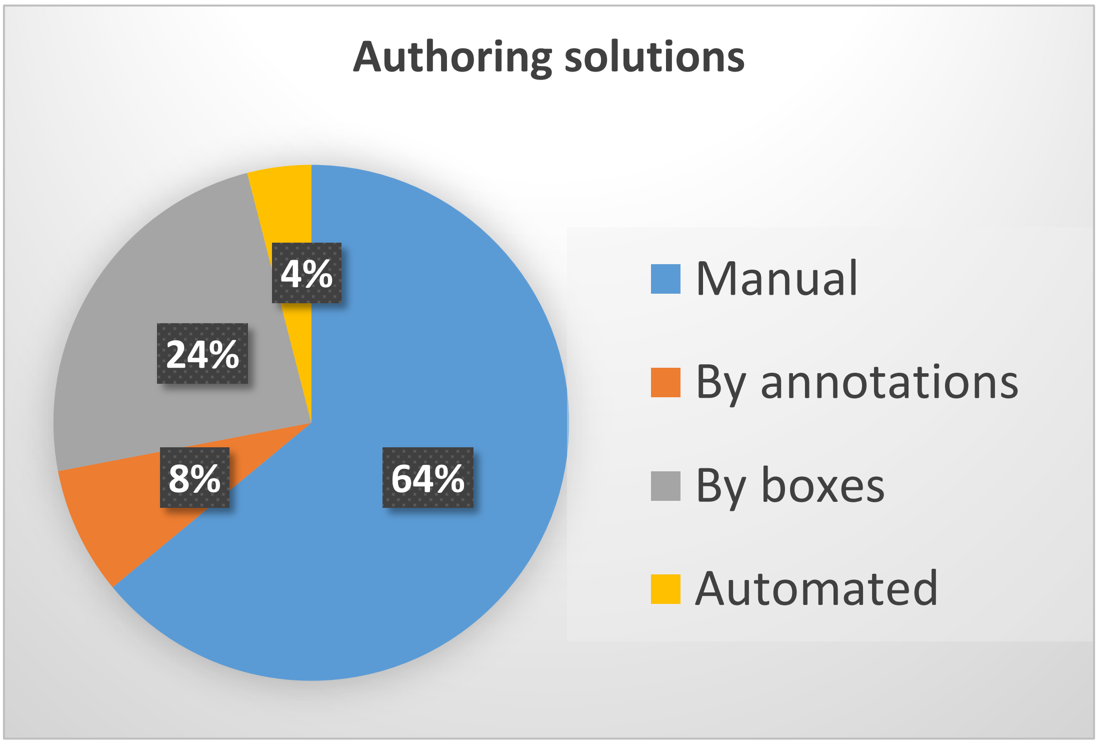


Figure 2.22. Authoring solutions mentioned throughout the 30 articles of this SLR.

In order to provide a more practical solution to the authoring problem, several authors developed different methodologies which in this chapter are categorised as: by annotations, boxes and automation.

The first one is the capability of adding virtual annotations to a real environment. In this thesis, by annotations is meant what Klinker [43] identified as plant maintenance set of primitive tasks: highlight, label, display information (text), clear information, edit information, set compass, hide/show. For instance, 3D dynamic and static contents cannot be generated through annotations. Alvarez [19] proposed to attach them manually to an image and utilised SLAM techniques (Figure 2.19) for the correct registration into the environment. Jung [77] developed a web-based annotating system for attaching notes to 3D models in order to improve designers collaborations. Similar applications are discussed by Nee [46] who reports that annotations aim to improve design decision communication in a collaborative system.

The second method aims to build AR processes (task by task procedures) without a deep computer programming knowledge. To ease the understanding of the utilisation of this method, it is necessary to introduce the concept utilised by Havard [38]. In his research, he modelled maintenance operations for AR defining the following:

1. Entity: the smallest part of the system to maintain (e.g. Nuts, plates)
2. External Entity: the smallest part external to the system to maintain (e.g. Tools)
3. Actions: the activities to be performed (e.g. Push, pull)
4. Maintenance: a series of actions
5. Operation: list of maintenance operations.

Considering each one of these being in a box, switching the boxes or changing their order would lead to a different maintenance task or different operation.

Another example is provided by Fiorentino [22]. Even though utilising a different nomenclature, he designed an authoring tool which consisted of set of actions that could be recalled to the AR application though an excel table. In this way, he provided an authoring solution that does not require any programming skill. Similarly Lamberti [31] proposed a reconfigurable framework where he defined nodes (simple procedure step) and edges (transition between nodes).

A greater effort has been made by Zhu in his research about “A context-aware augmented reality system to assist the maintenance operators”[21]. He provided technicians and operators the access to the authoring log (Figure 2.23), and the capability of modifying the contents provided by the AR developer in each box. Even though most of the information is in a text format, Zhu designed an interface to insert media files, modify visual properties and apply rendering rules. The modifications applied by a technician have to go through a review process made by the AR developer before being accepted and shared with other maintainers.

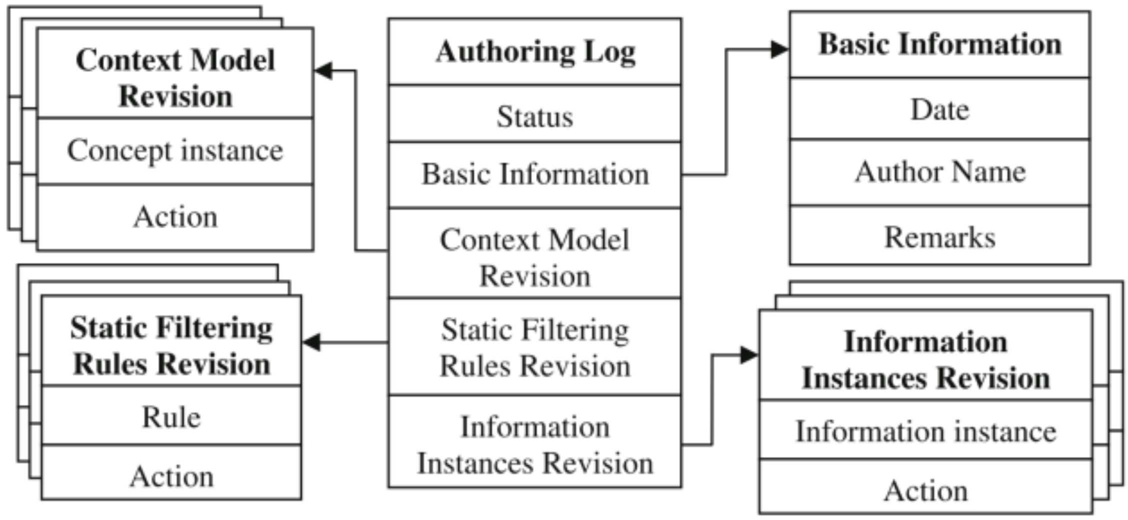


Figure 2.23. Technicians authoring log proposed by Zhu [21]. In the centre, the Authoring log. On the sides, the menu which are connected with different modules of the authoring log. This is visualised by the technician through a device and the interaction is made by buttons.

In any case, the smallest entities or nodes of an authoring solution by boxes have to be available or manually created. The reconfiguration of a procedure is limited to the boxes available in the system.

The relevance of considering the context conditions and develop a context-aware system are emphasised also by Erkoyuncu [78]. In his research, he developed and tested an authoring solution which uses real-time data from sensor to help building new authoring procedure through both a Context-Awareness Module (CAM) and a Context-Data Framework (CDF).

The last authoring solution and, the most ambitious one, is the automated authoring. This method has been applied only to assembly and disassembly procedures. These procedures are created automatically based on the CAD models and dis/assembly planning theory. Starting from all the possible configurations of the CAD model, Alvarez [19] has been able to automatically extract the disassembly procedure by merging the information of the disassembly-planning module and the CAD model constrains.

2.3.2 Answer to Q2: What are the AR future developments in Maintenance?

The answer to this question has to be found in the discussions, conclusions and future works of the papers analysed in this SLR. The question has been partially answered in sec. 2.3.1. Even though the advantages of the AR technology have been proven at an academic level, improvements are required in several fields in order to provide a robust, reliable and flexible solution for practical implementation [2], [12], [31], [72]. The main topics of research in terms of design and development in AR are:

1. Hardware (devices utilised for AR)
2. Recognition/Tracking (algorithms)
3. User-AR interaction
    a. Authoring solutions
    b. Contents management tools
    c. Visualisation and Ergonomics

These are described in detail in the following subsections.

2.3.2.1 Hardware future in AR for maintenance

The main hardware utilised in AR have been listed and described (Figure 2.10). Each device has some advantages and drawbacks. HMD are very promising for AR due to their mobility and the capability of overlaying the computer-generated information in front of the eye. Unfortunately they are still uncomfortable, have a limited FOV and may distort 3D images [12]. The limited peripheral visibility affects the safety of the operations, the virtual contents low-quality and distortion might cause sickness. HHD, even if portable, need a physical support system which does not affect the operations. Moreover, the dimension of their display only allows a restricted number of information to be overlaid. All the other devices lack mobility hence their application would not be suitable for all the operations performed by a maintainer [47].

All the devices available nowadays on the market for supporting AR systems lack in capabilities: power consumption, processing power, telecommunication, memory and resolution of cameras must improve [72].

Future hardware in AR will see a strong implementation of sensors and haptic devices. The first will enhance AR capabilities solving current obstacles. The latter will boost mixed-reality technology providing tangible feedback to AR users.

In a not so close future, we might see the utilisation of virtual retinal displays, AR contact lenses [72] and 3D holograms projectors.

2.3.2.2 Registration and Tracking' future in AR for maintenance

Tracking has been previously defined as the heart of the AR systems. Tracking techniques have been listed in Figure 2.19. All the vision-based techniques are affected by the environmental conditions such as lighting, occlusions, materials. For instance, lighting has been partially solved through histogram equalisation, but the accumulation of errors due to it still make the tracking not robust and reliable [32]. Future trends in overcoming the lighting issue involve the utilisation of CAD models for extracting the features (edges) of the virtual object and compare them with the real object captured by the camera. This process can be applied only for the initialisation of the AR system. Once recognised the object, the tracking has to work based on the image captured through the RGB camera.

Even though some tracking techniques can be more robust than others, in a specific application, their reliability is still not considered adequate to the industrial environment [2], [12], [26].

2.3.2.3 User-AR interaction future in maintenance

Finally, the User-AR interaction needs to be improved. The skills required for developing and maintaining an AR system nowadays include: programming, modelling, animator, knowledge management. Moreover, the fragmentation of the development platform is an issue for AR developers [72], [79]. In order to implement AR in industry, the AR system has to be easy to maintain and modify. New authoring solutions and contents management tools are required [35]. Reconfigurability of future AR system is a must, hence Authoring tools flexibility must improve [31].

An effort must be put in order to understand which the best way is of visualising the information based on the operation and the environment. Visualisation and vision-haptics visualisation should be explored [74]. The way information is brought to the maintainer has to be studied. Future trends include the utilisation of haptics modality to transfer knowledge to the operator [30].

Future AR systems must be adaptive. They should be able to systematically capture the user's intentions in performing a maintenance operation and collect the data of any maintenance procedure. The information collected could be used for improving the training process or the maintenance procedure itself [30].

2.4 SLR Research Gaps

In this section are reported the three main research gaps identified throughout the SLR and addressed in this thesis respectively in sec 3, 4 and 5.

1. Research gap 1: SLR has shown that the AR technology has been explored and tested mostly at an academic level. There have been a number of studies which aimed to quantify the benefits of AR in different industrial and maintenance application. Still, at the time of writing, there is not a common unified approach. Each of the studies found in literature has proposed its own AR application and tested it on real objects or mock-ups. Each AR application has been developed utilising different hardware, development platforms, programming language, software and user interface. This fragmentation has brought a lot of confusion in industry which does not have a clear understanding of the impact of the technology and does not understand what kind of technical investment it would involve. Therefore, overcoming the fragmentation or providing a clear method for letting industries easily approach AR could ease the implementation of AR in maintenance. In agreement with this first finding, the author of this work has developed and proposed a

methodology for selecting AR technology for maintenance and reported it in chapter 3.

2. Research gap 2: Even though the technology has shown a great potential in improving human performance in maintenance, the process for creating the digital contents necessary for running AR is mostly manual and time consuming (Figure 2.22). The experts refer to this problem as “contents-related issues”. Nowadays, in fact, several professional figures are required for creating AR contents: engineers that know the maintenance procedure, CAD modellers able to create the digital replica of the real object, animators able to produce the AR step-by-step procedure, programmers able to implement the digital contents within the AR application and many others. Several attempts have been done by different studies to overcome this issue by providing a method for the easy creation of AR content since it would de-skilling the authoring of digital contents for AR. In the current study FARP has been proposed in chapter 4.

3. Research gap 3: Finally, the utilisation of AR has been explored in different maintenance fields as shown in Figure 2.3. One of the less studied field of applications has been found to be Remote Maintenance (only 8%). Partially connected to the contents-related issues mentioned before, AR has not exploited his potential in remote applications. The quantification of the advantages in terms of spatial referencing and communication improvements have not been addressed by previous studies. The author believes that AR could boost spatial referencing in remote assistance and overcome current remote assistance tools such as voice-call and video-call. Strengthening the awareness that AR is a valuable technology for enhancing remote assistance, could increase the interest and investments in AR therefore ease the implementation of AR in maintenance. Augmented Reality for Remote Assistance (ARRA) has been proposed in this study in chapter 5.

2.5 SLR Conclusions and future work

The results of this SLR aim is the answer to two research questions: Q1) What is the current state of the art of AR application in maintenance for supporting human operators? Q2) What are the AR future developments in Maintenance? Based on the SLR the main fields of application and maintenance operations have been described. The current technology utilised has been outlined and a comparison among the 30 articles of this review has been provided. The main challenges for the implementation of AR in maintenance have been discussed answering the first question. Future AR directions and field of research have been reported and emphasised answering the second question. In general, the AR technology is still not mature for complying with industrial requirements of robustness and reliability. HMDs have to become more comfortable and powerful, tracking robustness has to be improved and contents-tools for AR have to be developed.

The three research gaps which are addressed in this thesis have been highlighted in sec 2.4. These have been synthetised from sec. 2.3.

Regarding the threats to the validity and objectivity of the SLR, the author provided a fully reproducible methodology which is subjective only in the application of the quality criteria.

It is worth to clarify that, in this study, the author applied the SLR methodology to each database separately and collated the documents selected just before the synthesis and analysis steps (see sec. 2.2.4). A different approach could be to collate the documents found in the different databases just before the application of the IC and EC. With the latter approach, in fact, duplicates would be identified earlier in the study and the workload would decrease. The final result will not be affected.

The data extraction process has been explained and applied systematically. When possible, the results have been validated through a comparison with other studies and/or reviews.

Therefore, the author believes this SLR provides a contribution to AR in maintenance. This could be used for anyone approaching AR at an industrial level as well as an academic research.

Future literature works could aim to find a correlation between AR systems and their application in a systematic way. It has been found there is no common architecture or standards to apply for AR in maintenance. Moreover, in the broader context of digital engineering, what is the role that will be played by AR compared to VR or Mixed Reality? Can we learn and accelerate the implementation of AR in industry based on the experience of VR technology?

AR is close to deploy its full potential, but as noted by this chapter there are a number of areas that require further improvements.

3 An Innovative Process to Select Augmented Reality (IPSAR) technology for maintenance

Abstract. Augmented Reality (AR) technology for maintenance aims to improve human performances by providing relevant information regarding both corrective and preventive maintenance. The development of an AR system involves the choice of a hardware, a development software and a visualisation method. These selections are challenging due to the wide choice of services and options available which result in fragmentation: different development processes and different user experiences.

In order to ease the selection of an AR system for supporting maintenance operations, this chapter proposes IPSAR: Innovative Process for Selecting AR. It guides the reader to identify the requirements and the constraints for any specific application through a number of questions developed in this study to help with the selection. This results in suggestions for the selection of the hardware, the development software and the visualisation method. IPSAR is built based on a literature study, grey documents and experts' interviews. IPSAR has been validated by comparing the choices made by non-AR experts using the proposed process with the choices made by AR-experts for the same case study. Future works could extend IPSAR to face the economical and ergonomics aspects related with the selection of an AR system. It could be done expanding the literature research including studies which investigate into the economical and ergonomics consequences of the application or AR for maintenance.

3.1 IPSAR Introduction

The aim of Augmented Reality (AR) technology is to enhance human performances by providing relevant information for a given specific task. AR can be utilised through any type of hardware able to interact with human senses: Tablets, Head Mounted Displays (HMD), Hand-Held Display (HHD), projectors and headphones. The reason for selecting a device rather than another is not always trivial, and it relates to the environmental conditions, the users and the process requirements. In the same way, the software architecture of the AR System might be selected based on considerations which vary among different industrial environments. For instance, while military could prefer to utilise "zero-connectivity" in order to ensure the cyber security, a commercial application could require connectivity for providing remote assistance. Finally, the user interface should be selected based on the user and the process requirements. It has to be mentioned that there is fragmentation between the providers of AR tools (hardware and software). It means that the combination of the devices, the Software Development Kits (SDKs), open-source platforms and the commercial ones available results in a high number of possible ways of developing an AR system, but the advantages and disadvantages are not always clear.

This chapter aims to propose a process that could guide the reader to select its AR system features and capabilities, as well as the development constrains.

Section 3.2 explains the methodology utilised for building the proposed AR decisional process for maintenance. Section 3.3 and 3.4 reports respectively the results and the validation. Section covers the conclusions, which includes the discussion and proposal for future works. Finally, Section 3.5 covers the conclusions, which includes the discussion and proposal for future works.

3.2 IPSAR development methodology

This section reports the methodology utilised for developing the process to select AR technology for Maintenance.

The methodology consists of 4 *Phases:*

Phase 1) Identifying relevant documents for the project.

Phase 2) Compiling AR systems characteristics tables.

Phase 3) Analyse tables.

Phase 4) Develop a process to select the AR system characteristics.

Each Phase is described in detail below in this section.

Phase 1: Documents identification

The first phase of the project has been identifying relevant applications of AR in maintenance.

A systematic literature review [1] method has been used to answer the research question: how are AR systems selected and developed for maintenance? The databases selected are: Scopus, ScienceDirect and IEEE. The initial string utilised for the searching phase has been: ("AR" OR "Augmented Reality") AND ("Maintenance"). Inclusion and exclusion criteria have been defined to narrow down the number of articles identified. This approach led to 25 relevant documents as referenced [14], [18]–[21], [25]–[29], [31], [33]–[39], [41], [42], [44], [45], [80]–[82] to answer the research question.

Phase 2: Compiling AR systems characteristics tables

Phase 2 consists of categorising the articles collected during *Phase 1* in a form which allows comparison and analysis.

Considering the aim of the project, each document has been screened to find any trends in the correlation between the hardware, development software, visualisation method (and user interface) selection and the case studies. It has been done by compiling a table for each article. In the rows are listed the hardware, the development software and the visualisation methods; in the columns are reported the description, the motivation statement and the comments. If required, a raw with another relevant feature has been added. In Table 3.1, provided as an example, a raw with the information about tracking has been added.

The tables have then been reviewed and modified in order to use a similar nomenclature on the cells for allowing the comparison process.

Table 3.1 Example of table compiled for one article. The article is reported in the top left corner.

Fiorentino (2014)	***Description***	***Motivation Statement***	***Comments***
Hardware	Projector 2.5m cameras	HMD not well accepted by the users: imbalance and weight; limited FOV; visibility of digital overlay.	
Development Software	Unifeye Engineer Visual basic	for industrial applications	
Visualisation Method & User Interface	animations text images		Bluetooth headset and speech recognition not acceptable due to the number of mistakes
Tracking	Marker-based (4x40mm + 1x140mm)	robust and accurate tracking	Not accurate if not calibrated

Phase 3: Tables Analysis

As a result of *Phase 2*, 25 tables, like Table 3.1, have been built. *Phase 3* consists in comparing the tables. It has been done cell by cell with particular emphasis on the “motivation statement” column mentioned in sec. 3.2. When the content of the same cell of the different tables were in agreement, the cell has been coloured in green, when in partial agreement in yellow, when in disagreement in red.

As outcome of this process, the main reason for the selection of each parameter can be listed.

Phase 4: Develop decisional process

This phase aims to develop the process for selecting a specific AR technology. Based on the analysis made in phase 3, the author decided to develop four questionnaires (sec. 3.3) and to provide the charts (Figure 3.1-Figure 3.4) for reading their results.

Firstly, based on the tables analysed in Phase 3, 93 questions have been developed to assess the AR system requirements. It has been noticed that each answer can affect more than one choice (hardware, development platform and visualisation method). Moreover, in order to ease the application of the process, the author aimed to simplify the questionnaire narrowing down the number of questions to 30 and dividing them by topic. The final output are 4 different questionnaires: one for assessing if AR could improve the operator performance, three for assessing respectively hardware, development platform and visualisation method. The four questionnaires are reported in sec. 3.3. The answer to any question would be a number from 1 to 10 respectively “completely agree” and “completely disagree”. These questions are the outcome of the correlation between the motivation for making a choice and the choice itself. For instance, if it has been proven through *Phase 3* that Head Mounted Displays (HMD) are utilised when the task duration is between 30 and 60 minutes, the question would be: does the task last more than 30 minutes? For a task that lasts on average 28 minutes, the answer would be 7-8 (disagree) depending on the variance of the phenomenon.

The results of these four questionnaires answers will be than analysed through the four charts below (Figure 3.1-Figure 3.4). The average answer of each table corresponds to a specific choice.

These charts have been designed considering the major trends and correlations found in the literature.

Once the average scores have been compared with Figure 3.1-Figure 3.4, a feasibility check is required to assess the compatibility between hardware, development platform and visualisation method. It has to be done case by case by checking the latest update from the provider and using the technical datasheet of the hardware and the development platform.

3.3 IPSAR Results

The result of this study is the process for selecting the AR technology for maintenance. The process consists in: four questionnaires (Table 3.2-Table 3.5) and four charts (Figure 3.1-Figure 3.4) for understanding the questionnaires results.

The questionnaires are designed for assessing the AR system requirements for a specific maintenance case/task. For more than one application, it is suggested to apply the process multiple times.

The answer to each question has to be a number 1 to 10 where 1 means “completely agree” and 10 means “completely disagree”. Following the nr.4 questionnaires.

Table 3.2 Questionnaire for assessing whether AR is required/feasible or not.

Questions	Score (1-10)
the task does not require concentration	
the duration or error rate variances are less than 10% among different operators	
flexibility among operators is not required	
the system to be maintained is complex	
live data is not required to perform the task	
the cost of maintenance is clear	
maintainers do not follow a standard procedure	
the maintainer carries out the same operation daily/often	
the operation is not in a remote location	
The object to be maintained is subject to degradation	

Table 3.3 Questionnaire for assessing AR system Hardware

Questions	Score (1-10)
the task lasts more than 30 minutes	
two hands are required to perform the task	
the task is not in a narrow space	
the task does not require wide FOV (field of view)	
the task involves flexible objects (hoses, wiring…)	
the location of the maintenance is remote	
the operation does not require gloves, helmet or glasses	
the task involves geometric alignment	
the task requires to connect the object to a computer	

Questions	Score (1-10)
cybersecurity and privacy are major drivers in operations	
the environment is wet or hot or extreme	
the object to be maintained is subject to degradation	
the colour/material and lighting conditions can vary on the object	
the operator position is fixed during the operation	
the task involves liquids	

Table 3.4 Questionnaire for assessing AR system Development Platform

Questions	Score (1-10)
the location of the maintenance is remote	
the task requires to connect the object to a computer	
cybersecurity and privacy are major drivers during the operations	
the colour/material and lighting conditions can vary on the object	
live data is required to perform the task	
maintainers follow a standard procedure	
the operation is in a noisy environment	
the maintenance database has to be updated after the task	
the operation is fail-proof	
CAD of the object to maintain are fully available	

Table 3.5 Questionnaire for assessing AR system Visualisation Method

Questions	Score (1-10)
the location of the maintenance is remote	
the task requires to connect the object to a computer	
is cybersecurity a major driver for systems selection	
the operator has been trained to perform the task (qualified)	
the operation is in a noisy environment	
the maintenance database has to be updated after the task	
the operation is fail-proof	

Questions	Score (1-10)
the task lasts less than 30 minutes	
two hands are not required to perform the task	
the task is not in a narrow space	
the task does require a wide FOV (field of view)	
the task involves flexible objects (hoses, wiring…)	
the operation requires gloves, helmet or glasses	
the task involves geometric alignment	
the time or error rate variance is more than 10% among different operators	
flexibility among operators is required	
the system to be maintained is complex	
the design of the components can change	

The four questionnaires are specifically designed to address the AR application in maintenance hence are not suitable for other fields of application (marketing, entertainment, health).

Even though some choices could appear obvious for someone that has been previously exposed to the AR technology, they are not for anyone. The questionnaires have been designed for non-technical person, with a knowledge regarding the maintenance operation. It has to be compiled considering a single maintenance operation. If more than one operation should be supported by the AR system, it would be good to compile the questionnaire for the main activities and then compare the results.

The scores of the questionnaires will then be analysed through the charts in Figure 3.1-Figure 3.4. It should help the reader understand whether AR should be utilised or not and which hardware, development platform and visualisation method should be selected. Even though the selection is made using an average value, all the Figure 3.1-Figure 3.4 show a trend in the selection. It does not mean that it is always possible to identify only one parameter which affects the choice. For each selection the author identified the trends and designed the questions in a way that the answer score would be increasing in the same direction.

Figure 3.1 is the chart for understanding whether AR could or should be implemented or not. The number to utilise is the average of the scores of Table 3.2. Figure 3.1 has been built considering the average between two trends: the feasibility and the usefulness. Most of the figure implies a situation of uncertainty. This is due to the fact that it is not easy to find any AR application which is undoubtedly useful and at the same time extremely easy to develop and update.

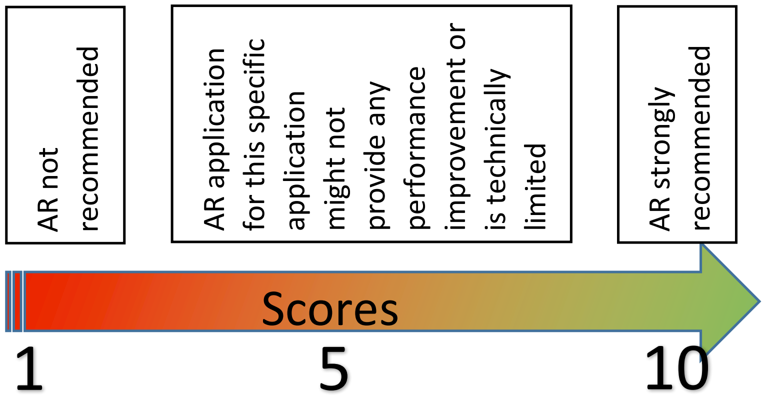


Figure 3.1 AR decisional chart.

Figure 3.2 is the chart for selecting what kind of Hardware/Device should be implemented. The number to utilise would be the average of the scores of Table 3.3. This chart does not get into the detail of the different devices available. Currently the market of wearable technology and augmented reality is rapidly evolving hence the author intent is to provide an insight of which of the main stream of hardware should be applied for the chosen case. For instance, despite the current technology, the category of HMD would always be more or less suitable in some specific cases. Figure 3.2 has been built considering mainly two trends: the flexibility and operator needs (requirements, safety).

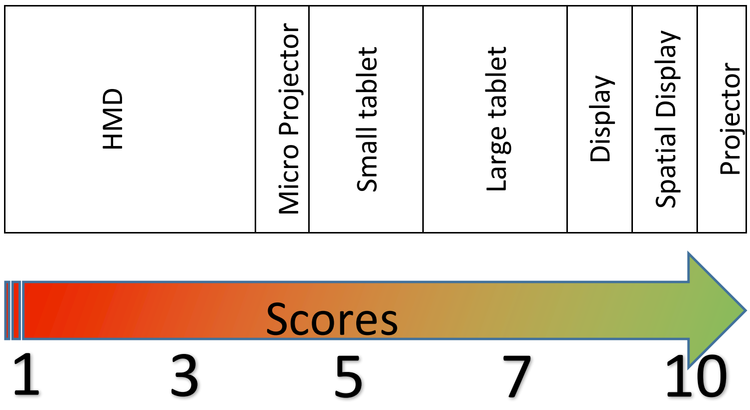


Figure 3.2. Hardware decisional chart for an AR system.

Figure 3.3 is the chart for selecting what kind of development platform should be used. The number to utilise would be the average of the scores of Table 3.4. For the development platform selection, the author decided not to give a specific name/brand, but to identify the main streams. It is relevant to consider that, the main key for this choice resides in the following two: the company capability and requirements under the IT point of view; The AR system complexity

It is obvious that it is always feasible to develop a software starting from scratches and using a very "low level" programming language. It could be useful, on the other side, to rely on a commercial platform which allows the internal IT department of a company to update and modify the AR tool at their convenience.

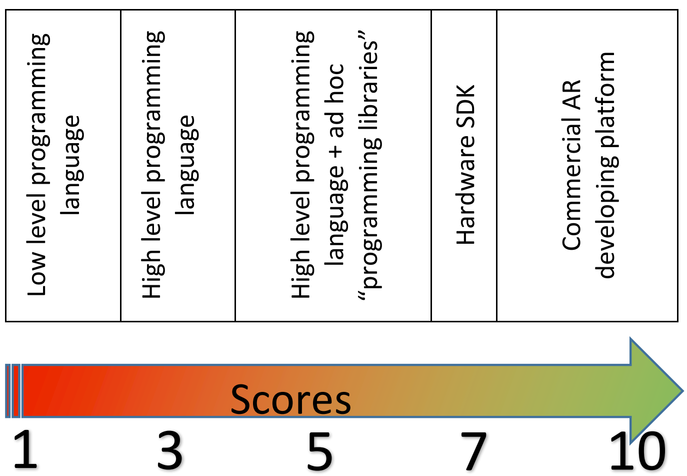


Figure 3.3. Development platform decisional chart for an AR system.

Finally, Figure 3.4 is the chart for selecting what kind of visualisation method should be implemented. The number to utilise would be the average of the scores of Table 3.5. From the left to the right, the author put from the most complex visualisation methods, to the easiest. The drivers for this selection are the complexity of the task and the maintainer requirements. As for the previous figures, also in this case the selection will be a trade-off among the drivers hence, for instance, if the task is very complex but the operator has been trained and carries out the operation daily, there would be no need to provide all the different kind of contents. It would add a not required complexity to the AR system.

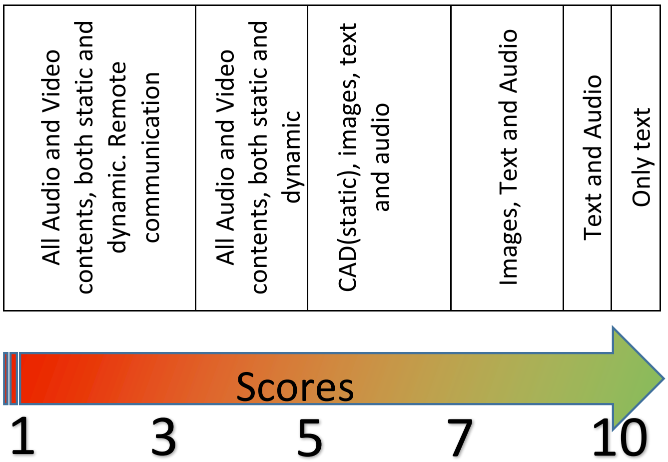


Figure 3.4. Visualisation method decisional chart for an AR system.

3.4 IPSAR Validation

This section reports the test carried out to validate the IPSAR developed within this chapter.

Firstly, the author has designed 5 maintenance case scenarios (7Appendix A) which are comprehensible without a strong engineering/maintenance background. These are reported summarised in and fully reported in 7Appendix A.

Table 3.6. Summary table of maintenance case scenarios 1-5 for IPSAR Validation.

	Who	*What*	*Where*
1	Not-expert mechanic / yourself	Change car's brakes pads	Properly equipped garage (light/tools)
2	10 yrs. experienced mechanic	Change car's brakes pads	Properly equipped garage (light/tools)
3	Windows IT technician	Change graphic board on Apple device	Properly equipped office (light/tools)
4	Not-IT expert, self-thought mechanical engineer	Fix hardware issue on consumer IT device	Tools are available.
5	Industrial technician expert. Not experienced on "machine A"	Maintain manufacturing "machine A"	Dusty and greasy machinery. Tools are available.

Each complete maintenance scenario utilised for validation is reported in 7Appendix A. and includes:

1. Description of the maintenance operation
2. Pictures of the maintenance scenario
3. "Who" is doing the maintenance operation (background and training)
4. "What" is the maintenance operation (complexity and occurrence)
5. "Where" is the maintenance carried out (environmental conditions)

The author has then asked to two groups of people to select AR for each of the 5 maintenance scenario.

The first group (G1) was composed of 5 engineering students who have been working on AR for maintenance for about 3 months. These have been considered as "AR experts" and have been asked to select AR by choosing on Figure 3.4 the score they considered right for each one of the 5 maintenance case scenarios.

The second group (G2) was composed of 5 engineering students who have never worked on AR. These have been considered as "maintenance experts" and have been asked to select the AR technology by answering the questionnaires in Table 3.1-Table 3.5 and then utilise Figure 3.1-Figure 3.4 to identify the chosen option.

The two groups' AR selections for the 5 case studies have then been compared by the author in Table 3.7.

Starting from the first case study. The two groups' selections have matched regarding the need for AR, the Hardware and the visualisation method. The groups have not agreed on the development platform. G1 has provided an average score of 7; G2 has provided an average score of 6. Even though these are close, they correspond to different selections in Figure 3.2. On the second case study, both groups both decided that there is no need to utilise AR. On the third case study the two groups did not match an both the hardware and visualisation method selections. On the 4th case study the two groups have not matched on the visualisation method and finally, on the last case study, there is a full match.

It has to be clear that, for validating IPSAR, the author wanted to check whether G2 selections made through the utilisation of the questionnaires match with the correct AR experts selections reported in the columns G1. Even though in some cases they did not match, the scores result to be very close.

Table 3.7 IPSAR validation results

Case Study Nr.	AR Y/N		Figure 3.2 HW		Figure 3.3 Dev. Plat.		Figure 3.4 Visual.	
	G1	G2	G1	G2	G1	G2	G1	G2
1	6	8	4	2	7	5	4	5
2	1	1	X	X	X	X	X	X
3	3	5	5	7	9	7	4	7
4	4	6	2	3	9	8	3	7
5	6	7	2	4	3	7	2	4

3.5 IPSAR Conclusions

This chapter presents IPSAR: an innovative process for identifying whether or not AR is recommended and what hardware, development platform and visualisation method should be selected for a specific maintenance task.

The novelty is that the author is providing a framework which allows non-AR-experts to take a top-level decision for selecting an AR system for a specific maintenance task.

The author believes an effort should be put in providing clear methodologies for both companies and academy, to better understand how and where AR should be used.

IPSAR has been developed based on a bibliographic study. The string utilised for the bibliographic study is: ("AR" OR "Augmented Reality") AND ("Maintenance"). Therefore, IPSAR, as presented, has been developed for selecting AR technology specifically in the maintenance field. It has not been designed to be used for selecting AR technology for other fields such as: entertainment, training, marketing.

IPSAR concretises in a set of 4 questionnaires which can be answered by a non-AR expert for a specific maintenance task. The questionnaires results have to be analysed through the 4 provided charts in order to obtain the preliminary AR technology design for the maintenance case analysed.

The validation of the process has been carried out. The case studies utilised for the validation are reported in 7Appendix A. It has shown that in most of the cases there is a match between the scores calculated through the questionnaires addressed by the non-AR-experts and the scores selected by the AR experts. In particular, there has been a full match regarding case study nr.5. IPSAR seems to be less efficient when selecting the visualisation method. It is the author opinion that this is due to two main factors:

1. the lack of detailed information regarding the case studies

2. AR experts are keen on always utilising AR animations to show maintenance procedures.

Future works should validate IPSAR on more complex real case scenarios. Moreover, the implementation in the process of a tool for assessing the economic and ergonomics aspects of the AR application should be included. The tool could be developed utilising the same methodology described in this chapter hence based on literature and validated through the comparison between the experts' selections and the process selections.

4 Fast Augmented Reality Programming (FARP): fast creation of AR step-by-step procedures for maintenance

Abstract. Augmented Reality (AR) has shown a great potential for improving human performance in Maintenance, Repair and Overhaul (MRO) . Currently, most of the studies are carried out only at an academic level. Industry still finds this technology not implementable due to limitations in three main aspects: the hardware limited capabilities, the object recognition robustness and the contents-related issues. This chapter focuses on the last one, proposing a new, low time-consuming and intuitive approach for creating AR step-by-step procedures for maintenance. The method developed and validated in this chapter has been named Fast Augmented Reality Programming (FARP). It is based on the assumption that AR can recognise and track all the objects in a maintenance environment and CAD models are available. The AR procedures created can be utilised to transfer knowledge to a non-expert maintainer. FARP has been implemented, as a software unit, in an AR system composed of commercially available hardware and open-source software. The system created has been tested on 30 participants. The results showed a time saving of 34,7% (min 24,7%; max 55,3%) and maintenance error reduction of 68,6% compared to the utilisation of hard-copy manuals. These have been compared with the performances of similar AR applications and the outcome is that procedures created utilising FARP are as valuable as the procedures created utilising the traditional AR contents creation methods. FARP's advantage is that any technician can create an AR step-by-step procedure with little effort. FARP not only eases the implementation of AR in Industry, but its intrinsic approach based on the data captured while performing the maintenance procedure, also opens the door for exploiting the full potential of AR for future intelligent learning data-based applications.

4.1 FARP Introduction

Augmented Reality (AR) is an innovative technology which aims to enhance the human perception of the reality by providing digitally-created contents in the real context [4]. Another definition has been provided by Azuma [15] who stated that an AR system should have three characteristics:

1. Combine real and virtual
2. Interactive real time
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 [2][15][69]. This chapter focuses on Maintenance, Repair and overhaul (MRO) operations.

MRO operations have a big impact on the lifecycle cost of industrial equipment [83]. The increasing complexity and automation of industrial machineries require new technologies for ensuring the reliability and productivity through MRO operations.

In the aviation field MRO operations cost can reach 80% of the entire aircraft lifecycle [31].

MRO operations strongly rely on the maintenance technicians expertise [63]. The latter can affect both the errors and completion time involved in the MRO operation thus influencing on the MRO cost.

AR could help reducing errors and completion time by allowing the easy access to MRO information which today belongs mostly to the expert maintainers' memory [60].

Even though the advantages (time savings and errors reductions) of AR in maintenance have been proven by academics, the technology still lacks robustness and flexibility to become of common use. Among the main research topics, in fact, it is possible to find [12][84][40]:

4. Tracking and recognition performances.
5. Hardware (head-mounted displays) capabilities.
6. Contents-related issues.

The last one consists of the difficulties related with creating and managing contents for AR applications. The traditional process of creating contents (authoring) for AR, in fact, requires several different professionals: programmer, animator, CAD modeler, AR developer. More innovative authoring solutions which provide a friendly user interface and contents adaptation have also been proposed [78][43][77][46]. Still, these require human effort and have limited flexibility.

This chapter focuses on easing the implementation of AR technology in maintenance by proposing a new method to create contents for maintenance procedures. More specifically, 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 providing a set of information gradually at each step of a MRO operation. The information considered in this PhD is visual (3D animations).

The method developed and validated in this has been named FARP: Fast Augmented Reality Programming. It takes inspiration from Fast Programming Robots, which allow users to teach robots by demonstration and without programming. In the same way FARP allows users to teach to the AR system how to overlay the virtual contents on the real environment without programming.

This chapter is structured as follows. Firstly, the research background and motivation are provided in sec. 4.2. Then sec. 4.3 describes FARP: how it works and how is it structured. The detailed methodology for FARP's validation is described in sec. 4.4. It includes the quantitative test design (sec. 4.4.1), the case study utilised (sec. 4.4.2) and FARP's implementation in an AR system for testing purposes (sec. 4.4.3). Analysis and results are reported in sec. 4.5. Finally, the discussion of the results, and the conclusions and future works are proposed in sec. 4.6 and 4.7, respectively.

4.2 FARP Research background and motivation

This research focuses on the creation of contents for AR (authoring) for maintenance applications. Authoring has been recognised as one of the main problems that prevents AR to become widely utilised [85]. The simple and easy creation of AR contents is not currently available. The authoring process is time-consuming and tedious and expensive [86]. The contents are now implemented in AR as “stand alone” programs by programmers [87].

The main issue is that current authoring environments require programming and graphical expertise [88]. The most common tools for authoring AR contents consist of plug-ins, software development kits (SDK) and graphical programming languages. Among these it is worth to mention Unity, Unreal, Panda3D, ArToolkit, Vuforia, Max/MPS. Nowadays, only few have attempted to ease and de-skill the authoring process.

Shim [89], in 2014 proposed an interactive features based AR authoring tool. This allows users to rotate, move, enlarge merge and occlude virtual object the virtual objects visualised over a 2D printed marker. The mentioned transformations are done through marker interaction and gesture interaction. Similarly Yang [90] in 2016 proposed an authoring tool which takes advantage of a mobile device to interact with the virtual objects visualised through a HMD. Both of these approaches do not require any programming skill and are not time consuming for the contents creator. Still it does not allow the creation of animation, which have been found to be very powerful in the maintenance environment [31], [38], [91]. It has to be mentioned that step-by step animations might not always be required [92].

Gimeno [93] proposed SUGAR as an easy-to-use AR editor which does not require programming skills. Still part of the content’s creation has to be done through the SUGAR editor. The latter requires the contents creator to input the picture of the working environments and manually create or import the virtual objects and animation that he/she wants 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 author's opinion that the method proposed by Gimeno is still time consuming.

Zhu [21] proposed an on-site authoring tool which allows the maintenance technicians to modify or create "information instances" related to maintenance procedures. This means that only text information can be created and edited.

Other authoring solutions have been used or proposed in literature [6], [19], [39], [74] but the author belief is that, even though the research interest in AR authoring solutions has been increasing, still the current methods are tedious, time-consuming and difficult to be implemented in 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 [86].

4.3 FARP

Fast Augmented Reality Programming (FARP) is a method which aims to overcome the contents-related issues previously described and therefore easing the implementation of AR in industry. Its name, in fact, indicates that, if implemented in an existing AR system for maintenance, it would allow "fast programming". In this context, "fast programming" means "fast AR contents-creation for maintenance procedures".

From now on, we will refer to any AR system for maintenance implemented with FARP as FARPIS: FARP Implemented System. FARPIS is a tool for easy knowledge transfer from expert to non-expert technicians within procedural operations (e.g. dis/assembly, repair, inspections). More specifically, 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 FARPIS would be suitable for any operation involving humans, e.g. both preventive and corrective maintenance.

FARP is based on two assumptions. The first one is that current object recognition and tracking issues [84] will be solved by providing reliable and real-time tools able to identify objects independently from the light condition and the background noise. The second hypothesis is that CAD models are available for the components involved in any maintenance procedure.

Sec. 2.1 describes how FARPIS works giving a practical example. Then, sec. 2.2 describes FARP's method in detail.

4.3.1 How FARPIS works: a practical example

It is the author's belief that the best way to explain FARPIS's concept is through an example. The FARPIS shown in this example has been developed using commercial hardware and open-source software. These will be described in sec. 4.4.3. The procedure selected is the assembly of a mock-up designed and utilised for testing purposes. It will be described in Sec 4.4.2

Firstly, consider the maintenance environment shown in Figure 4.1. It includes the maintainer (nr. 1), the product to be maintained (nr. 2) and FARPIS (nr.3).

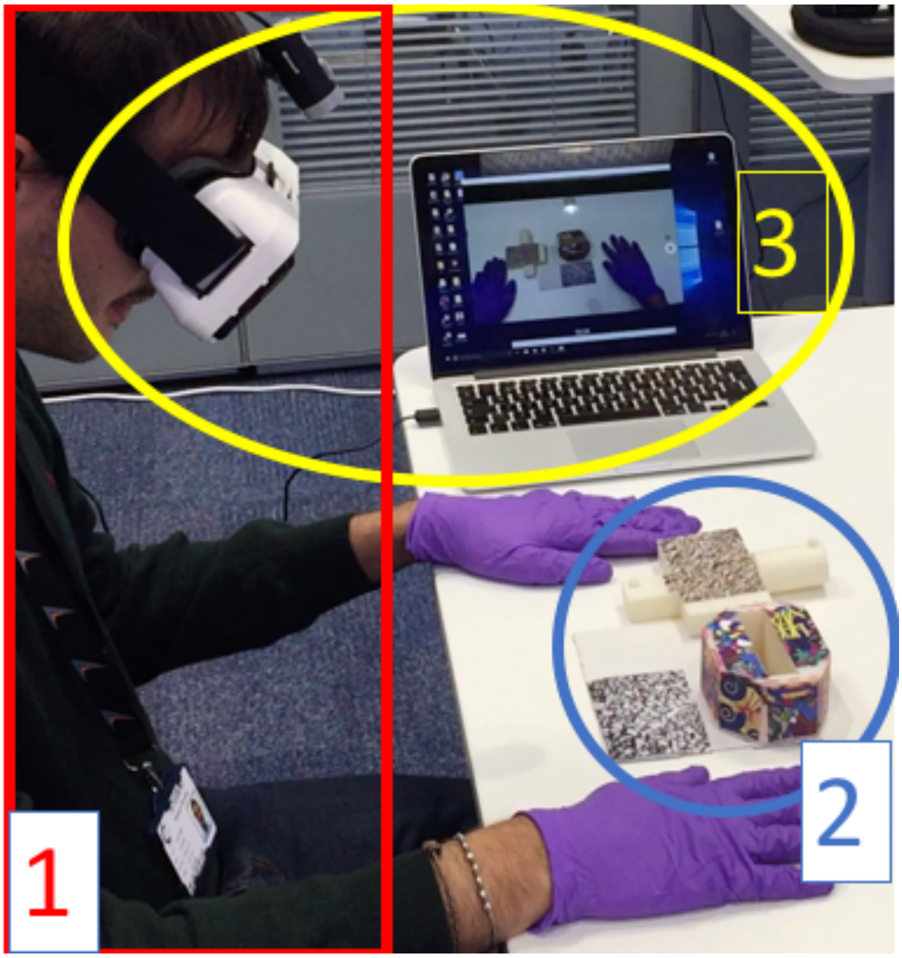


Figure 4.1. Maintenance environment simulation for testing purposes. The environment includes the technician (Nr.1), the product to be maintained (Nr.2) and FARPIS (Nr.3)

At this point we have two possible scenarios:

1. involving an expert technician,
2. involving a non-expert technician.

4.3.1.1 Scenario 1 – Expert technician

In this scenario FARPIS "captures" the expert technician knowledge.

The expert has to carry out a maintenance procedure that he/she is confident with, on the product shown in Figure 4.1 (Nr.2). He/she accesses FARPIS through the hardware provided. In this case, it is a "head-mounted video-see-through display".

Before starting the procedure, he/she will be able to select “record mode” to “capture” the procedure and select a name: e.g. “Procedure 1”.

Once started the procedure, FARPIS will simultaneously perform three actions:

1. Recognise and track the real objects in the Field of View (FOV) of the technician.
2. Store the transforms of the real objects in the table dedicated for “Procedure 1”.
3. Overlay the virtual objects over the real ones utilising the “basic overlay rule” available on a database (db).

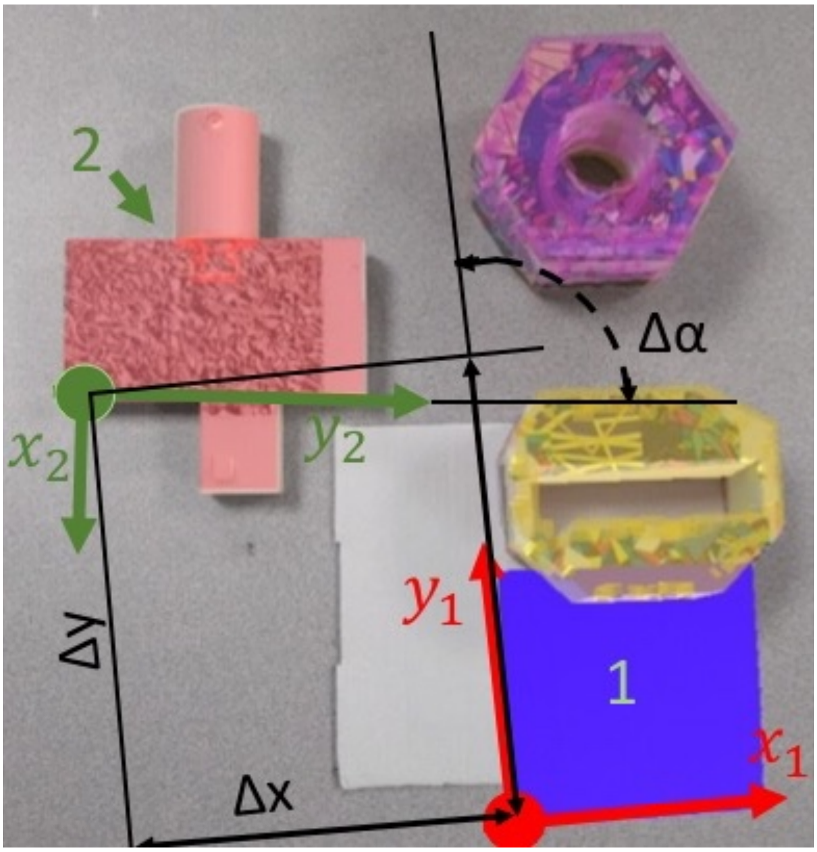


Figure 4.2. 2D graphical representation of “transform”. The transform vector of object 2 is ($\Delta x, \Delta y, \Delta \alpha$).

The first action consists of tracking the position and orientations of the objects. The second one means that the positions and orientations are stored as “transform”. A transform is a vector which consists of the linear and angular distances between an object (e.g. object 2 in Figure 4.2) and an anchor object (e.g. object 1 in Figure 4.2).

The third one refers to the capability of an AR system to overlay a virtual object on a real one following the predetermined rule. The basic rules of alignment and scale, as well as the rendering information, are called, in this thesis, basic overlay rule.

Once the procedure is completed, the expert technician can quit the “record mode” through the UI.

FARPIS will automatically build the AR step-by-step “Procedure 1”. The “How” is explained in sec. 4.4.

It is clear that the maintainer effort in creating the AR step-by-step procedure is very low. In fact, his/her only duty is to press the record button and perform the maintenance procedure as usual.

It is worthy to mention that no video-recording is performed by FARPIS.

4.3.1.2 Scenario 2 – Non-Expert technician

In this scenario FARPIS suggests a “step-by-step” AR procedure to a non-expert technician.

The non-expert operator has to do a maintenance procedure that he has not done before on the product in Figure 4.1. He/she accesses FARPIS through the hardware provided. In this case, it is a head-mounted video-see-through display.

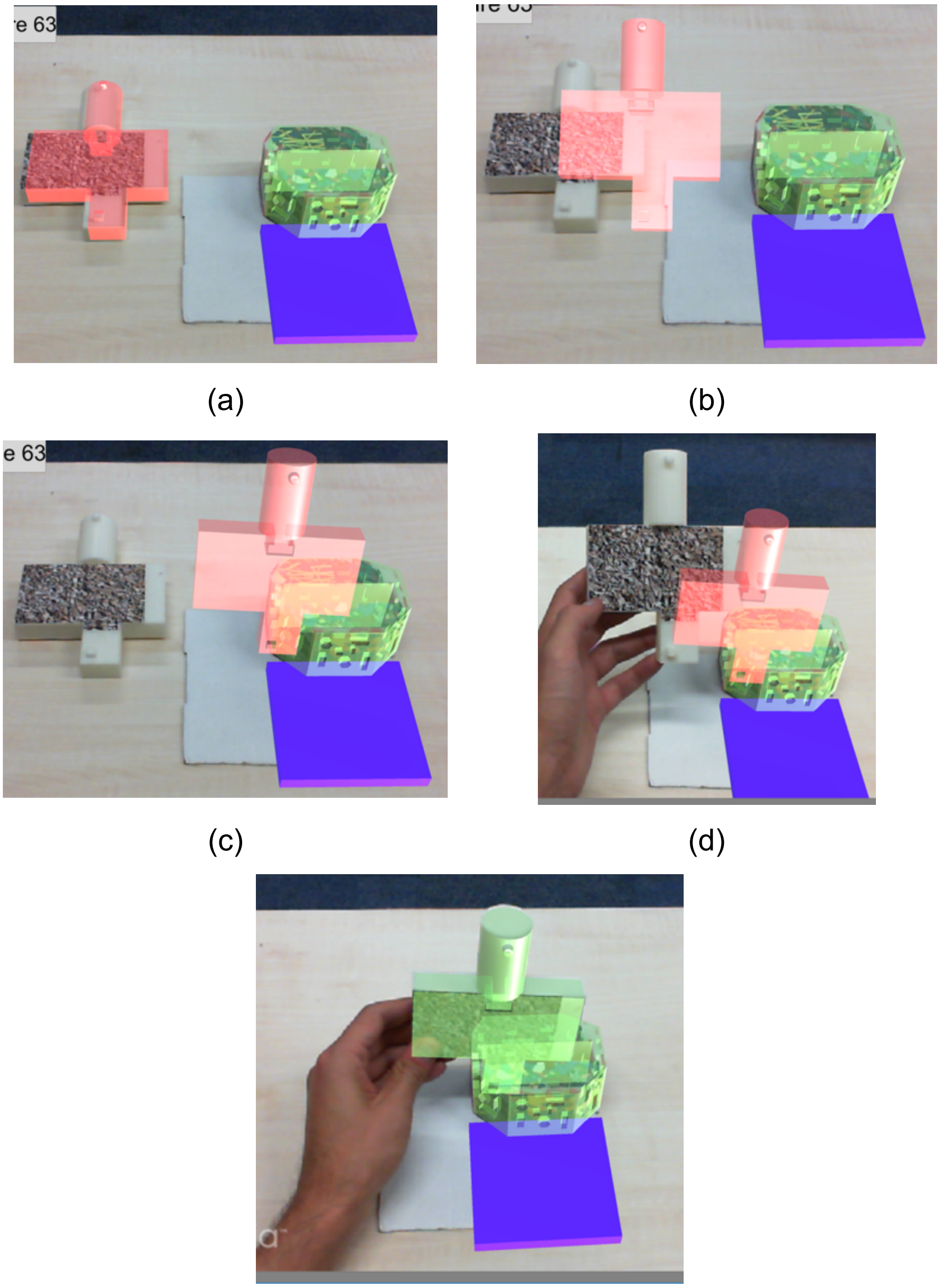
Before starting the procedure, he/she will select “play mode” and input the procedure name he wants to perform (e.g. “Procedure 1”).

At this point FARPIS will:

1. Recognise and track the real objects in the Field-Of-View (FOV) of the technician.
2. Overlay the virtual objects over the real ones following the basic overlay rule.

3. Find “Procedure 1” in its database (db .
4. Show the step-by-step AR “Procedure 1”

The latter consists in animating the virtual objects on the real ones suggesting the positions and orientations that the real objects have to reach at each step. An example is reported in Figure 4.3.



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

Figure 4.3 AR step by step procedure animation example.

Firstly, FARPIS recognises the objects and overlays the correspondent virtual objects utilising the basic overlay rule available on the db (Figure 4.3a). Then the virtual object animates detaching from the real object and moving to the target position and orientation as suggested by the selected procedure (Figure 4.3b, 3c and 3d).

When the technician puts the real object in the target position, the virtual object will become green (Figure 4.3e). FARPIS will then move to the next step of the procedure showing the next animation. When the procedure is completed, the screen shows the message “Procedure Completed”.

4.3.2 FARP method

FARP is a method that, integrated with an AR system, forms what in this thesis has been named FARPIS. 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. overlay the virtual object over the real one by overlapping the corners). FARP on the other hand provides the maintainer the ability to produce the virtual overlay rule by collecting the data from the MRO. This formalises the AR step by step procedures. FARP method is schematised in Figure 4.4. The figure is divided in three main squared areas: FARPIS, AR system and FARP. This division is meant to show that the union of an AR System and FARP method becomes FARPIS.

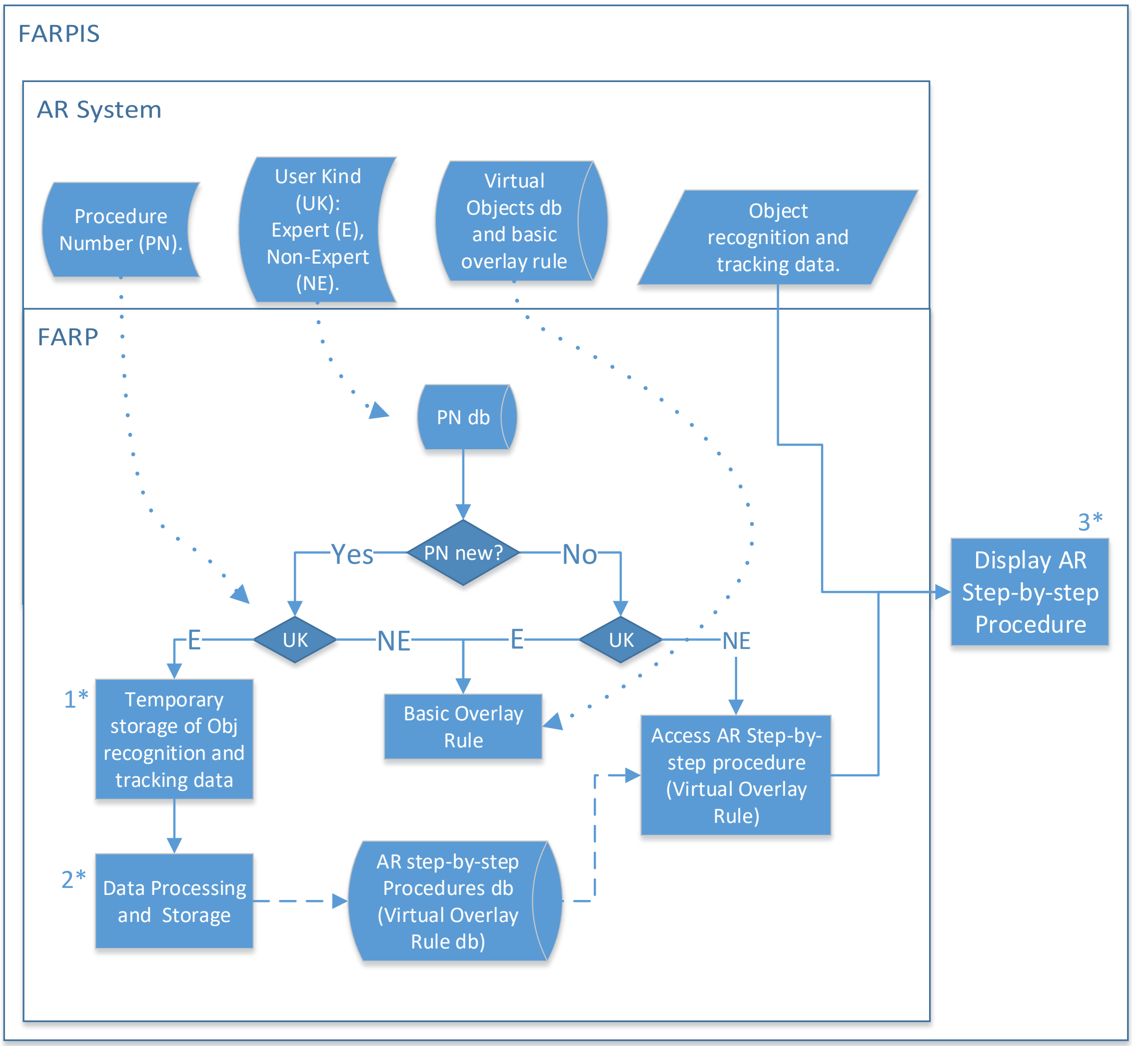


Figure 4.4. FARP method schematically represented within a FARPIS. The arrows in and out represent respectively the inputs and the outputs of each process.

In simple words, FARPIS consists of an AR system (hardware and software) which utilises FARP to record and display AR step-by-step procedures. The inputs (arrows in) required by FARP are the AR system outputs (arrows out) reported on the top of Figure 4.4:

1. The objects recognition and tracking data.
2. Virtual object overlay basic rule
3. The User Kind (UK).
4. The Procedure Number (PN).

The first input consists of the geometrical transforms in space related with the objects in the environment. Usually an AR system, in fact, can recognise an object and track it by estimating its pose: relative position and orientation of an object in space with respect to the camera. These can be translated in a transform relative to an anchor object in the scene.

The second input consist in 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 FARP only considers two levels of users: 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 any input from the operator.

Having all these 4 inputs, FARP will firstly check the procedure id and then the user experience level. Only in two cases, FARP will proceed. More specifically, if the procedure id is not already available on the db and the user is experienced, FARP will go through the processes “1*”,”2*” in Figure 4.4. This is the scenario described in the practical example in sec. 4.3.1.1.

On the other hand, if the procedure is already available on the db. and the user is non-expert, FARP will go through process “3*”. This is the scenario described in sec. 4.3.1.2.

In the other two possible combinations, “new procedure/non-expert user” and “available procedure/expert user”, FARP will not go through any process.

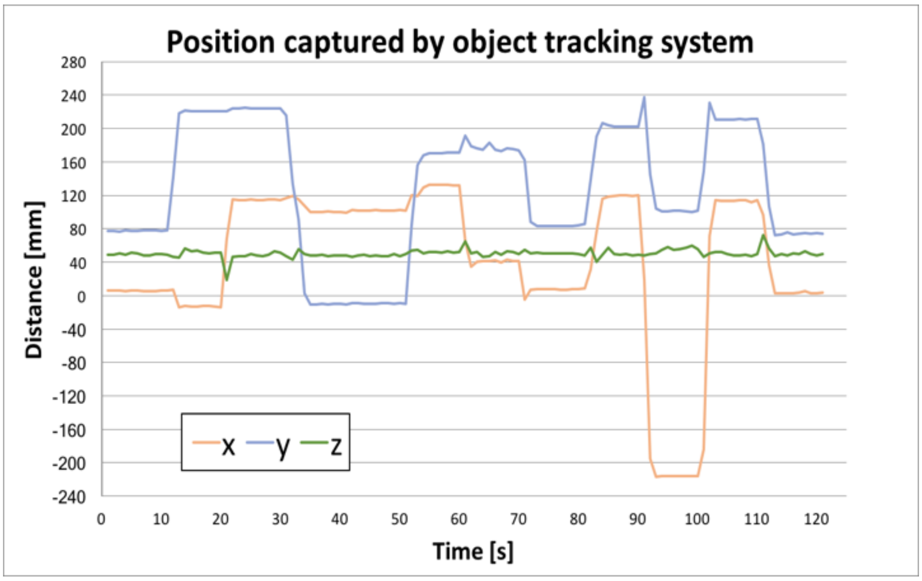
While process “1” is commonly utilised for software development, processes “2”, and “3”, in Figure 4.4, have been designed for FARP. These are described respectively in sec. 4.3.2.1 and 4.3.2.2.

4.3.2.1 Processing data

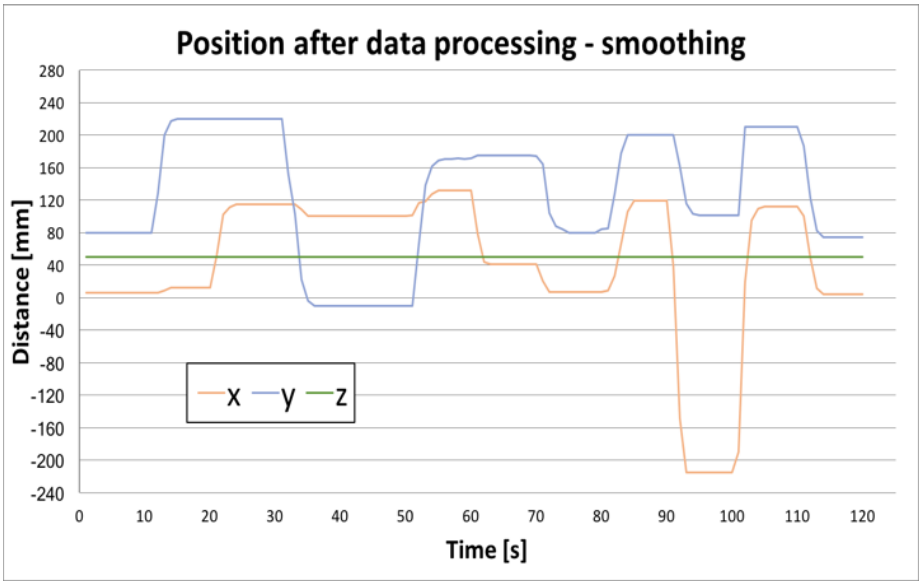
This process modifies the data acquired by the AR system and temporary stored at process “1” (Figure 4.4).

The “raw” data is acquired in real-time. We can imagine it as progressively filling the rows of a 2D table as the time advances. Each row has the object recognition and tracking information related with one of the objects in the environment at each time t_i. FARP is a geometrical based method. Hence, the information utilised are (x, y, z) positions and (α, β, γ) rotations. As stated before, these together build the transform vector (x, y, z, α, β, γ). An example of the data collected for one object within one MRO is reported in Figure 4.5a. For simplicity, rotations are not shown.

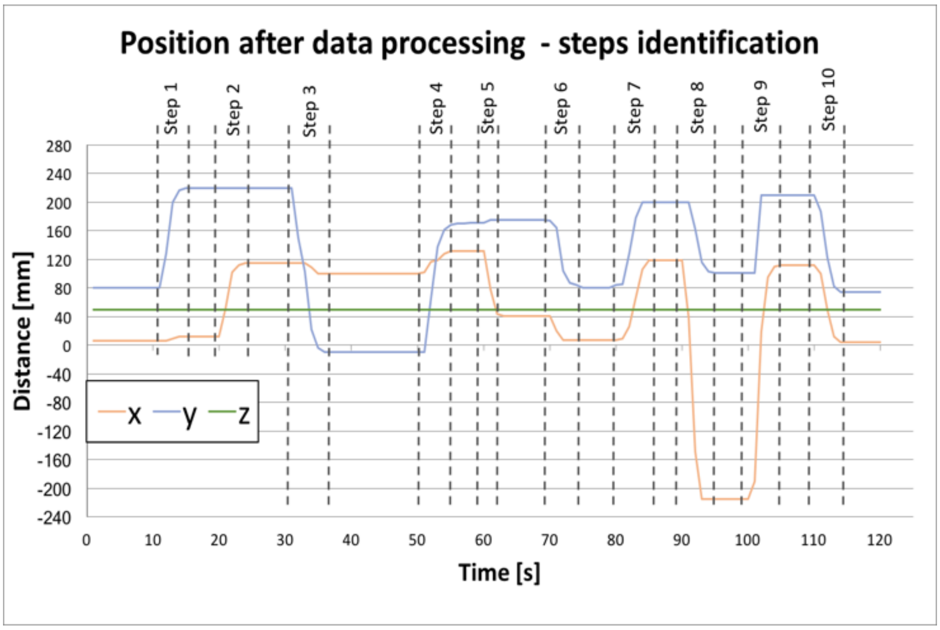
The data acquired is then smoothed (Figure 4.5b). The data acquisition, in fact, will have different errors due to the object recognition and tracking system. These have to be deleted or modified in order to store the correct information. In this example, due to the dimensions (distances and time) of the case, the author used an exponential smoothing, applying a threshold of 40 mm and 2 seconds. It means that any transformation in 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 and based on the author’s experience for this specific case. The process can potentially be automated.



(a)



(b)



(c)

Figure 4.5 Data processing applied by FARP in process 2* shown in Figure 4.4.

Once the table is corrected, process 2 will divide the transforms in groups in order to identify the procedure steps. For splitting the steps, FARP 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 Figure 4.5c, it is possible to see that “Step 3” has been identified between the non-variation of (x, y, z) after “Step2” until the re-stabilisation of (x, y, z) that follows the variation of y from 220mm to -10mm.

It is worth to clarify 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, it represents the AR step-by-step procedure.

4.3.2.2 Show AR procedure overlay rule

This process aims to create and show the step-by-step AR procedure created to the non-expert operator. An example of a step-by-step procedure has been reported in Figure 4.3.

The process for its creation takes three inputs:

1. the live stream of object recognition and tracking data.
2. the transforms table corrected and updated with the steps created in process “2”.
3. the 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” (Figure 4.4). 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 Figure 4.3.

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.

4.4 FARP Test design and methodology

FARP has been described in sec. 4.2. Its advantages in terms of time saving and low-effort requirements for creating AR step-by-step procedures have been described (see Sec 4.3.1.1). It is now essential to validate if FARPIS' step-by-step procedures created with the method described in sec 4.3.2 are as valuable as the contents created utilising traditional methods (see sec 4.1). If so, it would be clear that FARP could provide a step forward to ease AR implementation in Industry and partially solve contents related issues providing an intuitive tool for creating AR contents.

The approach taken by the author to validate FARP's method consists of two steps:

1. **Quantification** of the average time and errors improvements of a maintenance procedure carried out by using a FARPIS versus the same maintenance procedure carried out by using a hard-copy manual
2. **Comparison** of the results of the quantification with the average time and errors 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 4.4.1.

4.4.1 The quantitative test

This section describes the test carried out for quantifying the time/errors improvements within a maintenance procedure due to the utilisation of FARPIS versus a hard-copy manual.

The quantitative test methodology is described in Figure 4.6.

Starting from the top, the participant is asked to answer a short Likert scale (1-10) inclination questionnaire.

Table 4.1 Inclination Questionnaire.

Question	*Score (1-10)*
Experience with Digital Engineering	
Experience with Tablets	
Experience with AR	
Experience in Maintenance	
Experience in Dis/Assembly	
Experience with Puzzles	

A higher average score to the first three or the last three questions corresponds respectively 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 for maintenance-oriented profiles, the second for the AR oriented ones.

In the first case, the CC is then asked to carry out different MRO operations using a hard-copy manual (7B.1). He/she 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 using a chronometer and errors by filling a pre-designed form that lists the errors inserted in the mock-up. 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/she becomes an expert with performing the maintenance procedure. No data is collected in this phase.

The CC can now utilise FARPIS as described in sec 4.3.1.1 and create an AR procedure. This will then be utilised by the 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 a CC participant. During the latter, the observer will collect the time and errors data which will provide the FARP supported maintenance procedure “dataset2”.

In both datasets, time has been recorded in seconds and the number of errors has been stored. It is worth to mention that, as described in sec 4.4.2, 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.

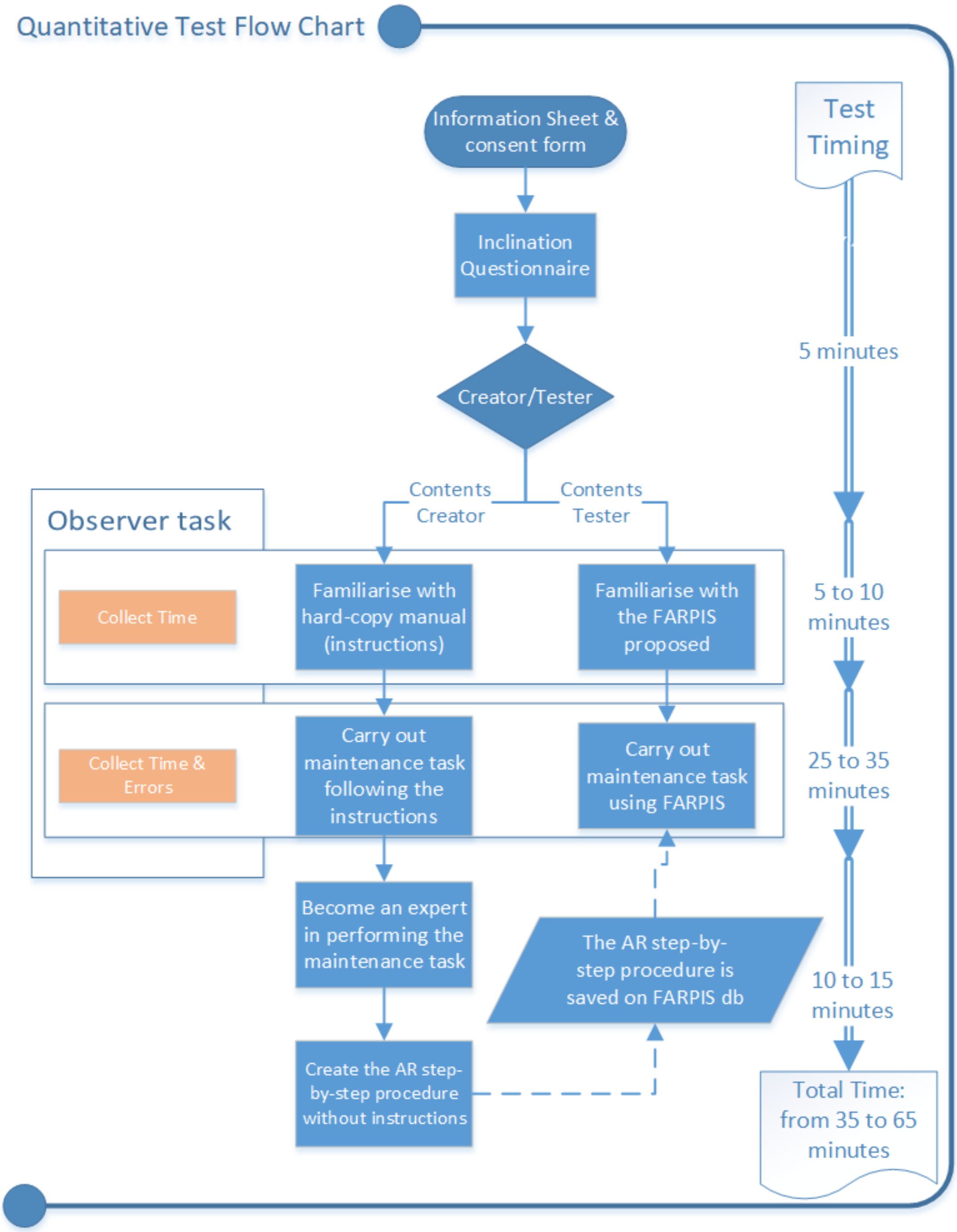


Figure 4.6. Schematic representation of the validation test.

“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 Sec 4.5.1.

The quantified results will then be compared with the ones found in literature related with traditional AR systems for supporting maintenance. Results are reposted qualitatively in Sec 4.5.2.

4.4.2 The maintenance case study for testing purposes

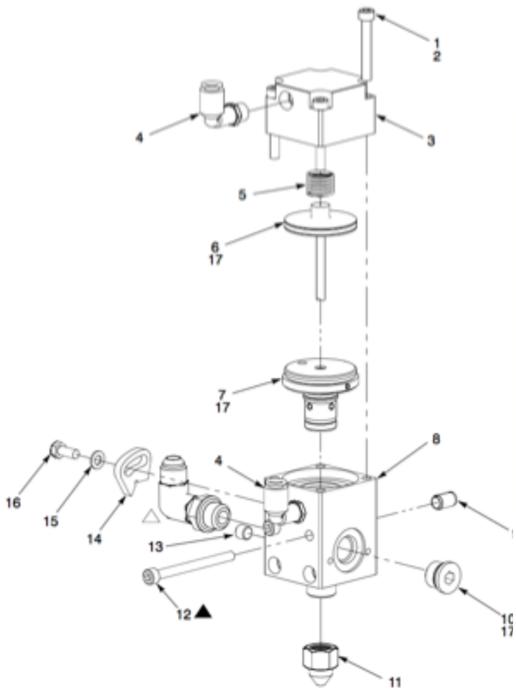
In this section the case study utilised for testing purposes is described.

The real case maintenance scenario chosen in this study is the dis/assembly maintenance of an hydraulic valve (Figure 4.7a) and linear actuator (Figure 4.7b).

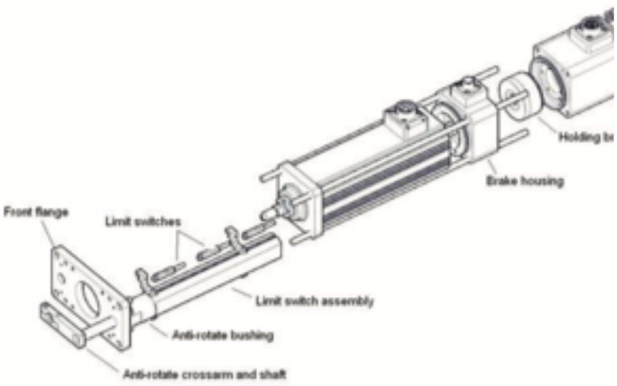
These assemblies, in fact, comply with what the author considered to be essential requirements for carrying out this academic study:

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 [84]
5. 3D printed simplified mock-up manufacturability

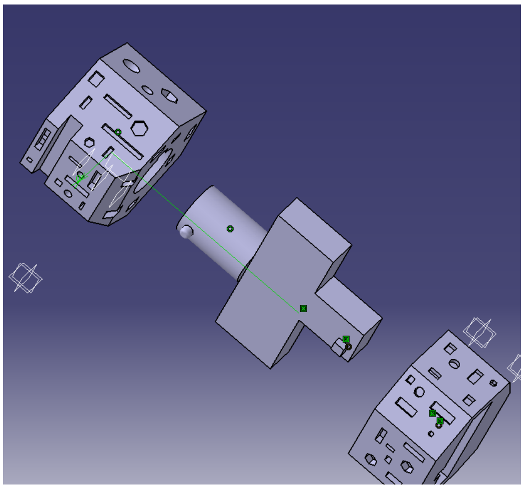
On the selected the case study, the author designed and 3d-printed a "maze" which has similar translations and rotations of its component. The mock-up CAD model is shown in Figure 4.7c and the 3D printed version is shown in Figure 4.7d.



(a)



(b)



(c)

(d)

Figure 4.7 Mock-Up designed for testing purposes.

The assembly consists of three components: the basement, the board and the top.

The basement has a planar maze which 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 maze in order 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 to the board.

It has a cylindrical maze which 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 author inserted three dis/assembly errors for testing purposes. These consist in the mis-placement of the assembly components with respect to each other in three different phases of the assembly.

For easing Vuforia's object recognition capability, the surfaces of the objects have been enriched with coloured stickers.

4.4.3 FARP implementation

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

4.4.3.1 Hardware

This section describes the hardware of the AR system where FARP has been implemented and become a FARPIS. These are shown in Figure 4.1.

FARP requires a hardware with input/output capabilities. FARPIS, in fact, has to collect data from the proposed environment and transfer the processed information to the operator through the output device. In this specific case, we have utilised an RGB camera and touchscreen as input device and a display as output device. Both installed on most of the commercial mobiles available. In this case, we utilised a 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, FARP's methodology could be utilised with different sensors and devices. For instance, rather than capturing the current environment with an RGB camera, it could also be possible to use a depth camera, infrared cameras. The input device could consist of a laptop or a head mounted display (HMD). As examples, Microsoft HoloLens or Epson Moverio HMDs could be used to meet these characteristics.

As input device, in fact, it is not unexpected that depth sensors will be soon utilised for a 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.

4.4.3.2 Software

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

1. hardware control
2. data processing and storage unit
3. provide a responsive user interface (UI).

It has been developed utilising Unity3D as game engine and Vuforia SDK and Android SDK. Moreover, a local virtual server with an SQL database has been set up to, not only provide storage to the information collected, but also process them offline easing the workload of the mobile device.

In order to ensure the reproducibility of the study, Appendix 7B.2 shows screenshots of db and Unity3D showing respectively structure and hierarchies. Moreover Appendix 7B.3 reports the main scripts, functions and query developed by the author for FARP.

4.5 FARP Analysis and Results

This section reports the analysis and the results of the test described in section 4.4. Firstly, results of the quantification test are reported in sec 4.5.1. Then the results of the comparison with current AR systems performances in maintenance are shown in sec. 4.5.2.

4.5.1 Quantification test

This section reports the results of the quantification test which aims to quantify the improvements due to the utilisation of FARPIS 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 industrials from "Cranfield University". The average age was 28.8 (20, 36, SD=4.28). As a consequence of the first inclination questionnaire (mentioned in Figure 4.6 and fully reported in Table 4.1) half of them have been asked to perform the test as CC and half as CT.

Each test took from 35 to 65 minutes for completion and all the data collected has been stored in compliance with Cranfield's research ethics policy.

The following subsections report the interferential statistical analysis and the results for the dependent variables "completion time" and "number of errors" affected by the utilisation of the FARPIS support vs. hard-copy manual support.

The statistical analysis has been carried out utilising SPSS. The dataset Is reported in Appendix 7B.4

4.5.1.1 Completion Time

In order to understand whether there is a statistically significant difference between the means of time completion of the maintenance tasks performed using FARPIS support vs hard-copy manual, the author decided to carry out the one-way ANOVA test.

The two different supports, as described in sec 4.4.1 are:

1. Hard-copy manual instructions
2. FARPIS

The maintenance procedures tested are:

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

The number of tasks and their characteristics have been chosen based on the case study described in sec. 4.4.2 and the author's experience.

In order to apply ANOVA to a sample, the normality and homoscedasticity of the latter has to be validated.

Even though it is generally correct to make the "assume of normality" for relatively big sized samples, in this study case it required to validate the normality. Since our sample is smaller than 50, we carried out the Shapiro-Wilk test and each task sample resulted normal since all the *p values* are greater than *0.05* as shown in Table 4.2.

The homoscedasticity of the sample has been validated applying the Levene test. Also, in this case, the *p values* resulted to be greater than *0.05* hence the samples have the same variance (Table 4.2).

Table 4.2 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	.226	.239
	AR(FARP)	.353	
Task 2	Manual	.347	.440
	AR(FARP)	.305	
Task 3	Manual	.119	.220
	AR(FARP)	.395	
Task 4	Manual	.305	.446
	AR(FARP)	.846	
Overall Task	Manual	.160	.129
	AR(FARP)	.623	

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 FARPIS improves the completion time of the overall task by 34,7% (501s vs. 768s) compared to the hard-copy manual support (Figure 4.8).

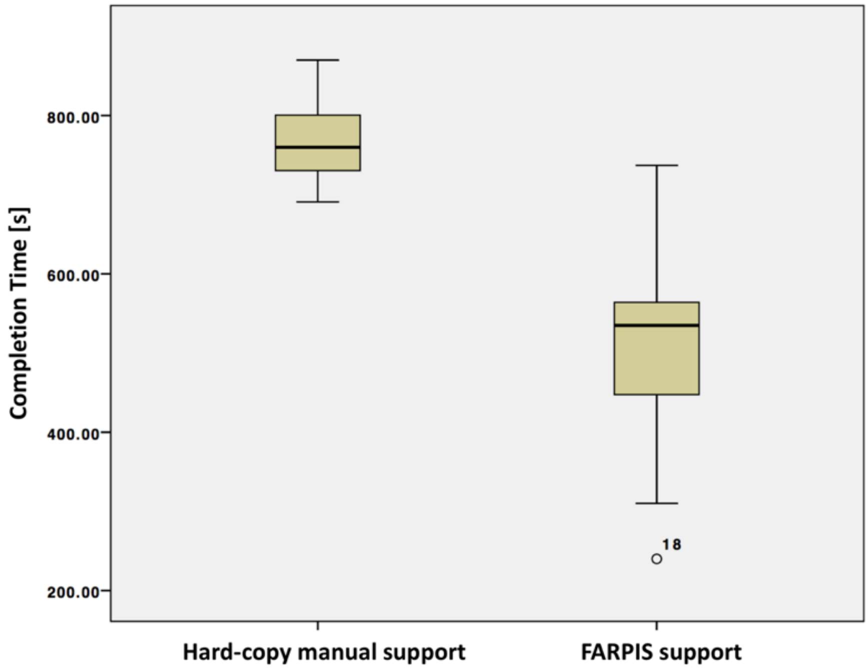


Figure 4.8. Overall task completion time with hard-copy manual and FARPIS support.

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)

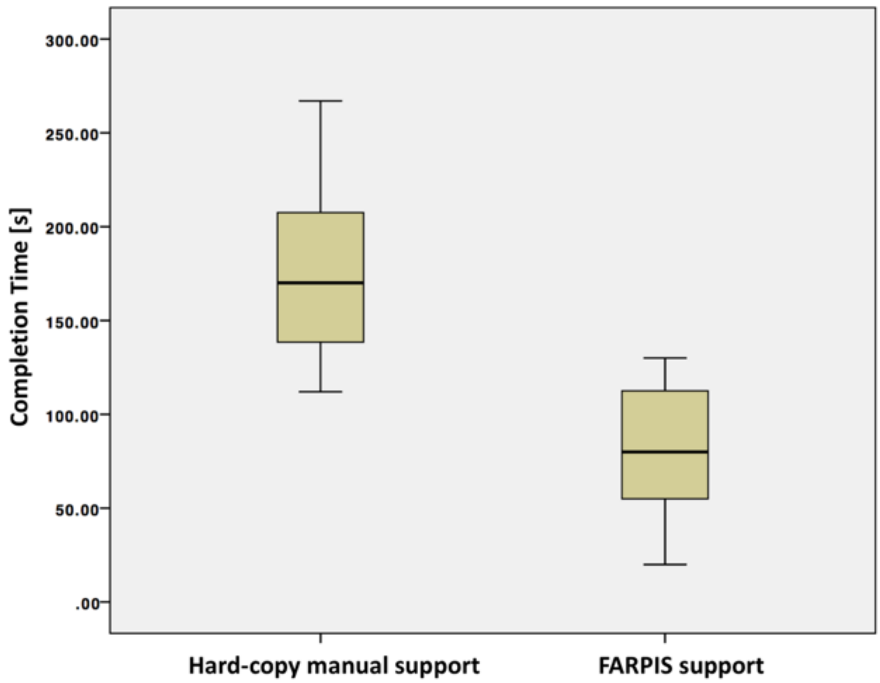


Figure 4.9 Task 1 completion time with hard-copy manual and FARPIS support.

Task2: F(1,28)=17.590 , p≤0.05 – 29,4% (209s vs. 296s)

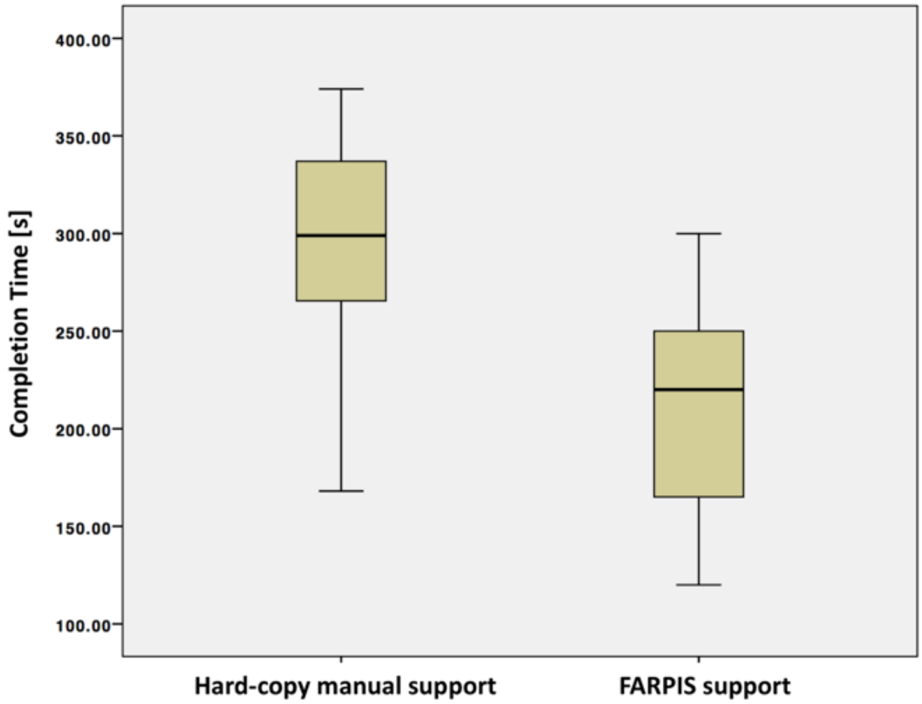


Figure 4.10 Task 2 completion time with hard-copy manual and FARPIS support.

Task3: F(1,28)=5.791 , p≤0.05 - 34,7% (145s vs. 222s)

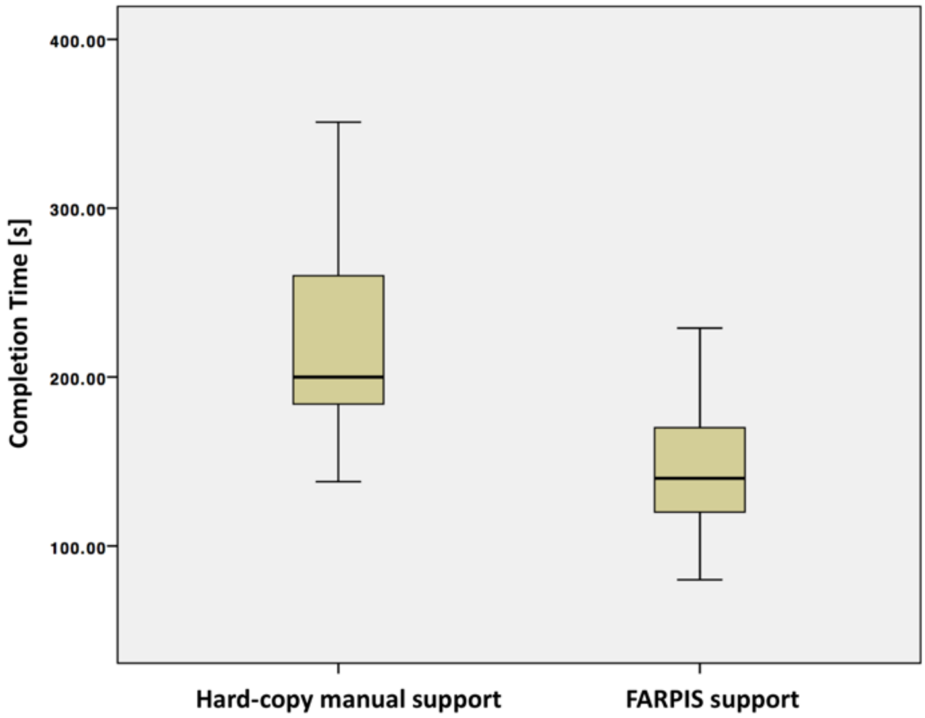


Figure 4.11 Task 3 completion time with hard-copy manual and FARPIS support.

Task4: F(1,28)=52.537 , p≤0.05 - 24,7% (67s vs. 89s)

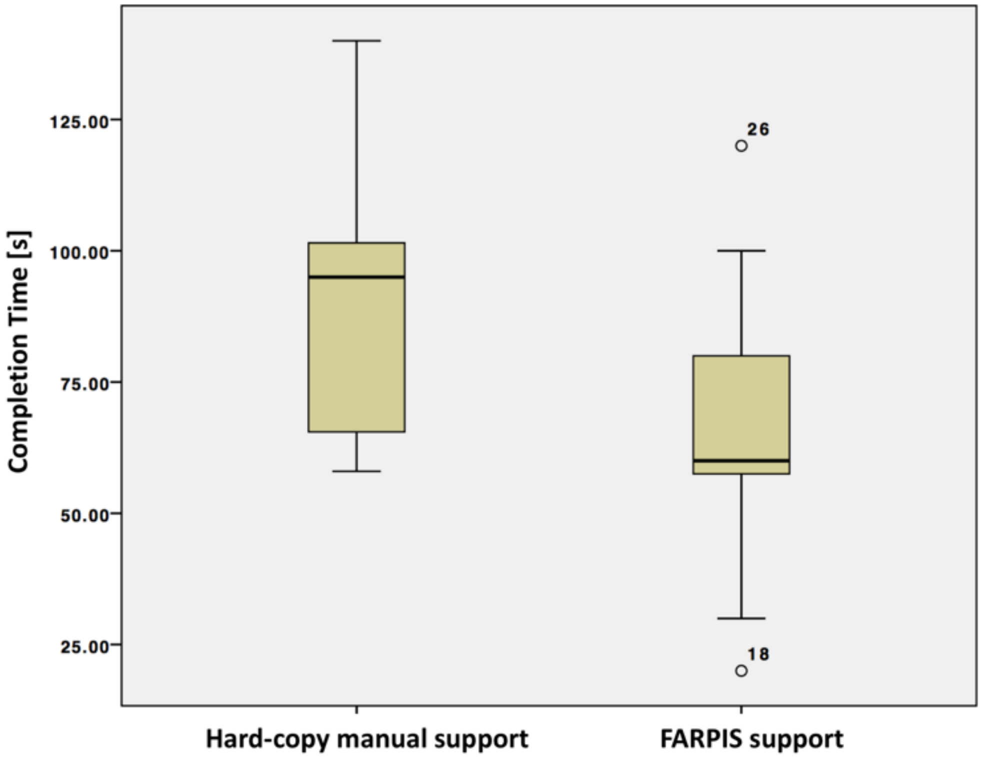


Figure 4.12 Task 4 completion time with hard-copy manual and FARPIS support.

4.5.1.2 Number of Errors

The approach utilised for analysing the number of errors collected is the same as the one utilised for the analysis of the completion time described in the previous section.

In performing the normality tests of the errors datasets, it has been found out 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 4.3, in fact, the p-values calculated through the Sapiro-Wilk test for the errors related to Task1, Task2, Task 3 and Task 4, are smaller than 0.05. Thus, it has not been possible to apply the ANOVA test to the singe tasks datasets. On a positive note, the overall task error dataset resulted to be both normally distributed and homogeneous in terms of variance.

Table 4.3 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	.003	.749
	AR(FARP)	.000	
Task 2	Manual	.001	.066
	AR(FARP)	.000	
Task 3	Manual	.000	.394
	AR(FARP)	.000	
Task 4	Manual	.042	.052
	AR(FARP)	.000	
Overall Task	Manual	.673	.200
	AR(FARP)	.126	

For the reason explained 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, $F(1,28)=30.919$, $p\leq0.05$ (95% confidence). Utilising FARPIS decreased the number of errors of the overall task by 68,6% (1,53 vs. 4,87) compared to the hard-copy manual support.

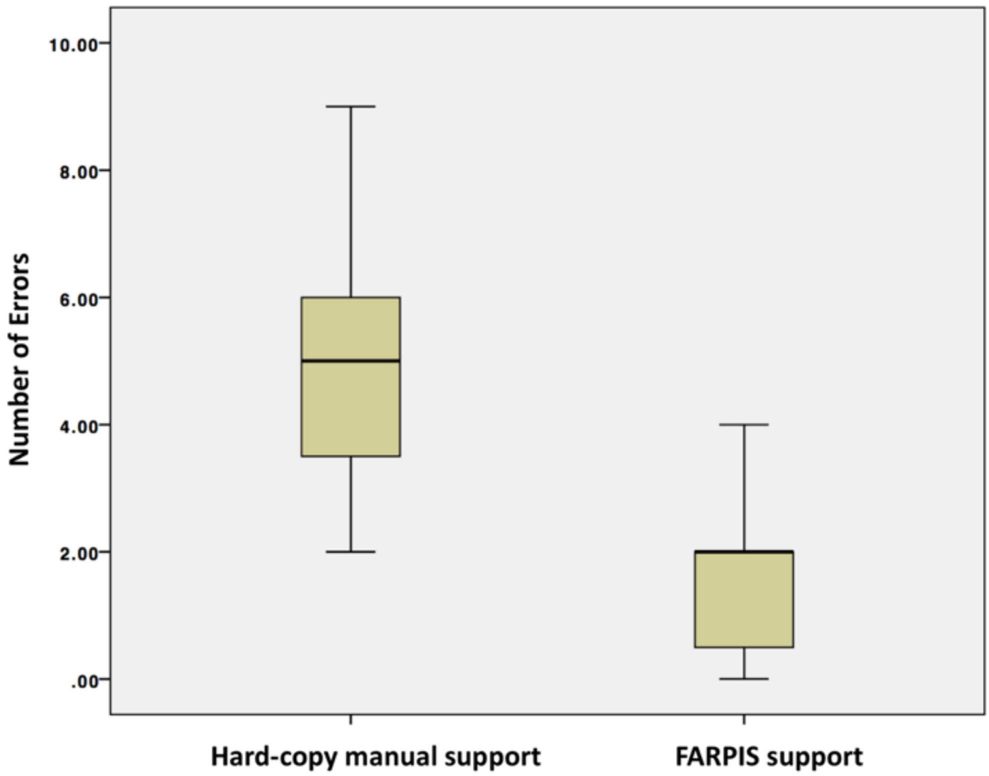


Figure 4.13. Overall task number of errors with hard-copy manual and FARPIS support.

4.5.2 Qualitative comparison results

This section reports the comparison between literature AR systems and FARPIS which have been quantified in sec 4.5.1.

FARPIS quantitative performance results are summarised in Table 4.4.

Table 4.4 Quantitative test result summary.

TASK	TIME REDUCTION	ERRORS REDUCTION
TASK1	55,3%	
TASK2	29,4%	
TASK3	34,7%	
TASK4	24,7%	
OVERALL TASK	34,7%	68,6%
AVERAGE	35.8%	68.6%

The time and errors reductions can be qualitatively compared with the ones found in literature and listed in

Table 4.5. The latter, in fact, as we did in this study, reports the results of the studies which compared the utilisation of AR system for supporting maintenance (designed and tested within their projects) VS the utilisation hard-copy manual supports.

Table 4.5 Maintenance performance improvements in terms of time and errors reductions found in literature.

REFERENCE	TASK	TIME REDUCTION	ERRORS RATE REDUCTION
LEE [94]	Accessing spare parts information	45%	
FIORENTINO [22]	Disassembly	38% (22.4% min)	92.4% (87.5% min)
RAMIREZ [20]	Aircraft maintenance	50%	
SANNA [25]	Notebook Dis/assembly	7%	70%
HENDERSON [14]	Task localisation	46.7%	
TANG [95]	Puzzle dis/assembly	26%	82%
ONG[2]	Inspection	50% to 66%	
HENDERSON [96]	Accessing information	16%	42% (not significant)
AVERAGE		35.5%	71.6%

Qualitatively comparing Table 4.4 and

Table 4.5, it is possible to understand that FARPIS' performance is close to literature AR systems. More specifically the average time and errors reductions obtained when utilising FARPIS is similar to the ones obtained in literature.

4.6 FARP Discussion

In this section the discussion about FARP validation methodology and the results are reported.

The author's intent in developing FARP is to provide a method for allowing technicians to create AR step-by-step procedures while performing the task and with as little as possible additional effort.

FARP, as stated before, is based on two assumptions:

1. Robust and reliable object tracking and recognition.
2. CAD models are available.

It is the author's belief that both these assumptions will be validated in the future. Current researches, in fact, are working on objects recognition and tracking solutions which, though the utilisation of new sensors and technology (depth cameras, cloud point etc.) will overcome current lighting and background noise issues.

It has to be mentioned that, one limitation of FARP and in general of AR systems will remain the recognition of similar and symmetrical objects which have different internal composition (e.g. two spheres with different weight but same radius).

The second hypothesis can be considered generally true for the industrial environment.

FARP has been described as a method and its implementation in an AR system has been named FARPIS. The intent in having two acronyms (FARP and FARPIS) is to emphasise the difference between the method (FARP) and its actual practical utilisation once implemented in an already existing AR system (FARPIS: FARP Implemented System). Even if different FARPIS can be proposed (as described in sec. 4.4.3.1), it is the author's belief that this would not negatively affect the result of the test reported in this chapter. The FARPIS proposed in this project, in fact, has been developed to comply with the minimum requirements in terms of performance and user interface because the aim of this project was to validate FARP and not the AR system.

In order to validate FARP, the author quantified its performance and compared it with the literature findings.

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: Tang [95], Fiorentino [22], Henderson [14]. For these reasons, even though for relatively small samples a non-parametric approach such as the Friedman test would be recommended, the author still preferred to assume of normality and homoscedasticity based on previous studies results.

The average time reduction in performing the test's maintenance tasks in sec. 4.5.1.1 (FARPIS VS hard-copy manual support) is 35.8% (Table 4.4). The biggest time reduction has been observed on Task 1. The author believes this is due to the fact that the participants who had to perform Task 1 with the hard-copy manual needed to take confidence with the manual itself. On the other side, the participants performing Task 1 with FARPIS intuitively followed the instructions on the screen.

The average error reduction (FARPIS VS hard-copy manual support) is 68.6% (Table 4.4) 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 has to 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. Still, the application of FARP method for repair, inspections and overhaul operations seems feasible and needs further investigations.

The methodology for comparing FARP's performance results with other literature studies is not as strict as those used for quantifying time and errors reductions.

This is due to the fact 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 a more effective validation of FARP as authoring method, it should have been directly compared with the authoring methods developed by other research centres and applied on the same case study. Unfortunately, this process would have required, not only the access to the conceptual authoring methods, but also the access to the actual tool that different research centres have utilised for the validation. This includes the software and hardware. This approach for validating FARP seemed impractical and not suitable at this stage of the study.

4.7 FARP Conclusions and future works

FARP is a geometrical based method for authoring AR contents for maintenance. It is based on two assumptions: 1) machines are able to recognise the objects in a working environment, 2) CAD models are available for all the real objects involved in the maintenance procedure.

The main contribution to knowledge in this chapter resides in the fact that FARP is intrinsically low time consuming and not-tedious since it does not require the maintainer do anything, but only performing the maintenance task. At the same time, it has been empirically proven that FARP can provide a similar amount of time and errors reductions as other AR systems for maintenance. For these reasons the author considers FARP as a step forward in the development of authoring solutions for AR (for maintenance but not only). It does not require any programming skill to be operated.

FARP has been presented and its validation has been reported in this chapter. The proposed method can be applied to any AR system and has to be implemented as a software unit. It allows users to create AR step-by-step procedures with little 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 to expand the FARP method to take more advantage of the information stored.

The validation should also 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 FARP 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 FARP and when utilising other authoring tools but all applied on the same case study.

In Figure 4.14 is reported the proposed future expansion of FARP.

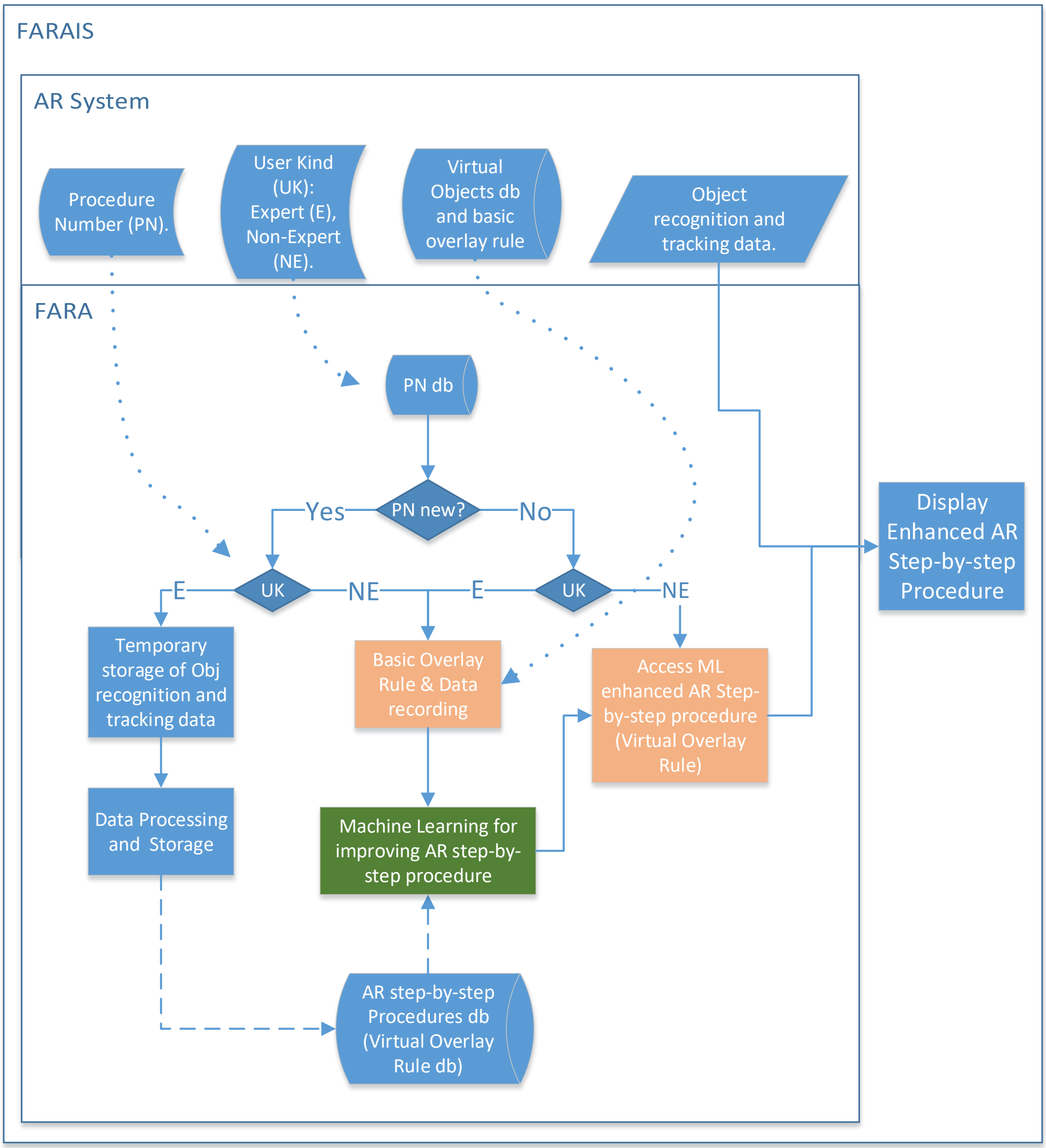


Figure 4.14. Schematic representation of proposed future work: FARP method implemented with Intelligent Learning (highlighted in green).

Comparing Figure 4.14 with the current schematic representation of FARP (Figure 4.4), it is possible to see one new processes: ML for improving AR step-by-step procedures (in green). Moreover, two processes have been updated and represented in the orange boxes. 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, in fact, FARP could potentially, classify the MRO operation steps and propose a different solution to a similar maintenance problem, without the need of an expert training.

5 Augmented Reality for improving spatial referencing in Remote Assistance: ARRA

Abstract. The advantages of utilising Augmented Reality (AR) technology for supporting maintenance operations have been widely investigated by academics. AR reduces the technicians' cognitive effort mainly resulting in both time and errors rate reductions. Still, its application in remote assistance has not been fully explored yet. This chapter focuses on understanding what the best benefit of providing assistance to a remote technician by means of AR could be. Augmented Reality for Remote Assistance (ARRA) has been designed and developed. It allows a remote novice maintainer to request for assistance and communicate with a remote expert through an AR system. 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. These have been asked to perform an assembly/disassembly operation on a mock-up of a piping system. The participants have been remotely assisted through ARRA or videocall 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 videocall 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 Point Of View (POV) since it relies only on the real environment configuration. The videocall support, on the other side, relies on the ability of the technicians to communicate and to understand each other's POV. Future studies should investigate into quantifying the improvements due to other factors involved in remote assistance, especially language barriers and connectivity issues.

5.1 ARRA Introduction

The increasing complexity of industrial machineries due to the constant push for improvements in productivity and reliability of industrial facilities, has provided a flourishing ground for research and innovation [21]. Internet of Things, Digital Engineering, Smart Factory, Virtual Reality, Digital Twins, Augmented Reality (AR) are only 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 [97].

In this study, we explore the utilisation of AR for Remote Assistance (RA) applications in maintenance. Several definitions of AR are provided in academy. The first and most widely recognised one has been provided by Azuma in 1997 [98] and restated in 2001 [99]: “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 [83] and strongly rely on the maintenance technicians’ expertise [63]. In this scenario, AR technology for RA can potentially allow the “de-skilling” of the remote maintenance operations and, at the same time, improve flexibility and costs of maintenance [36]. The flexibility, in the maintenance scenario, is the capability of performing MRO operations without specific skill-requirements, location constraints and effective with unexpected events [100]. The cost would be directly affected by avoiding the need of time consuming and expensive maintenance training as well as travelling [101]. In is not uncommon, in fact, that machineries vendors are required to provide assistance in remote locations because their technicians are better trained to preform MRO on the vendor’s product (industrial machineries, tooling, instruments). Similar maintenance dynamics may occur also within different departments of the same company.

In order to provide such benefits, the AR RA tool should overcome three main limitations of current RA technologies based on voice and video call support [102]:

1. spatial referencing – identifying the correct location and orientations of 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 chapter focuses on improving spatial referencing through the utilisation of AR for RA. The author developed an AR approach which puts in communication two technicians situated in different locations: the expert and the remote novice. The AR approach has been called ARRA: Augmented Reality for Remote Assistance. It is based on the assumptions that the AR system is able to recognise and track the objects in the Field of View of the novice and that the CAD models of the objects to be MRO are available. ARRA allows in execution-time order: 1) the novice to request assistance, 2) the expert to visualise virtually on his/her real environment, the objects to be MRO, 3) the expert to manipulate the virtual object in order to build a step-by-step MRO procedure 4) the novice to visualise the step-by-step MRO procedure and 5) the expert to monitor the progress of the MRO procedure.

ARRA has been validated through empirical testing and comparison with traditional videocall assistance.

This chapter is structured as follows. Firstly, the research background and motivation are provided in sec. 5.2 .Then sec. 5.3 describes ARRA: how it works and its technical development. The detailed methodology for ARRA's validation is described in sec. 5.4. It includes the description of the case study utilised (sec. 5.4.1) and the quantitative test design (sec. 5.4.2). Analysis and results are reported in sec. 5.5. Finally, the discussion of the results, and the conclusions and future works are proposed in sec. 5.6 and 5.7, respectively.

5.2 Background: Augmented Reality for Remote Assistance

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 [84][46][103]. 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 [84]. 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 utilisation of AR or other technologies ((VR, the Cloud, Computer) [54], [57], [104].

Bordegoni [105] in 2014, proposes 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 customers satisfaction, cut costs and allow rapid intervention always considering low connectivity.

Cologni [106] in 2015 attempted to utilise Mobile Internet Devices (MID s) such as smartphones to remotely acquire data on a machine (equipped with its own electronics and monitoring sensors) and apply corrective actions if required. The corrective actions can be suggested by the remote manufacturer or maintainer by mean of AR annotations and/or directly modifying the machine parameters. This method requires a gateway architecture which is not always available and applicable only on heavily electronics equipped machineries.

Oda [102] 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. Still Oda does not consider this solution applicable for complex manoeuvres.

One of the most recent attempts to provide RA through AR has been done by Mourtzis [107] in 2017. His cloud-based system connects the assembly plant with the maintenance department. The MTBF of the machines to be maintained are 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 are built through the analysis of the physical constraint on CATIA. For instance, once the object to be maintained has been identified, the CAD model is automatically analysed on CATIA and the components’ DOF are 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 hence solve one of the main issues of the implementation of AR in maintenance: the AR contents creation [78], [85], [86].Still the author believe it to be slightly too simplistic. It, not only could provide different solutions for the same problem, but also it does not consider unpredicted events and does not take advantage of the human experience which is essential in maintenance [63].

The AR solutions for RA described testify 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 chapter, the author attempted to quantify the expected spatial awareness benefits resulting in the utilisation of AR for RA.

5.3 ARRA

Augmented Reality for Remote Assistance (ARRA) is our 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 is able to recognise and track the object in the field of view of the remote novice maintainer.
2. The CAD models of the objects to be maintained are available.

The author considers the assumptions plausible due to the recent advancement in image processing, depth sensors and CAD modelling [84][73].

On Figure 5.1 is reported a schematic concept of how ARRA works, what is the data flow and who are the main processes involved.

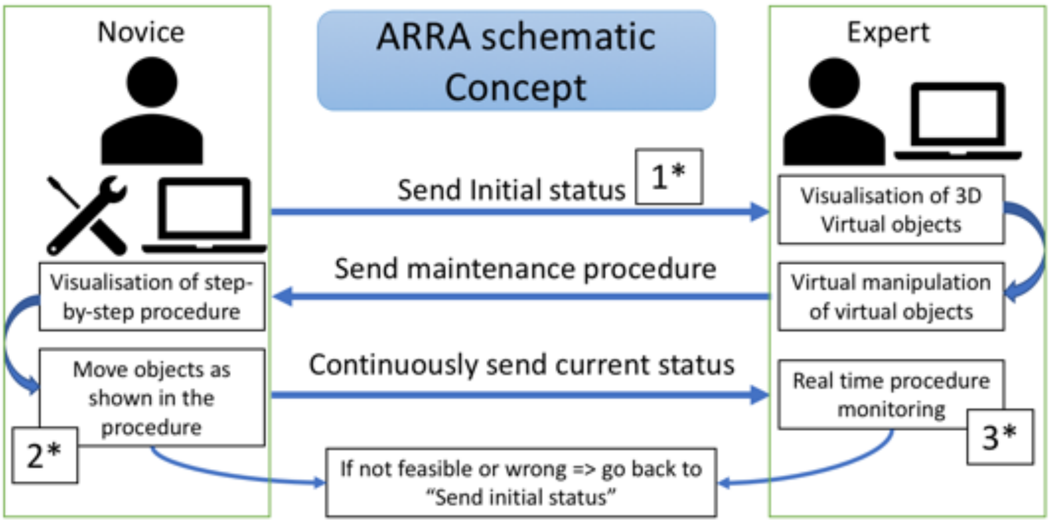


Figure 5.1 ARRA schematic concept and functionalities.

On the left, the remote novice maintainer who has to carry out a maintenance operation without having the complete 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 objects movements (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 objects' movements real-time (3*)

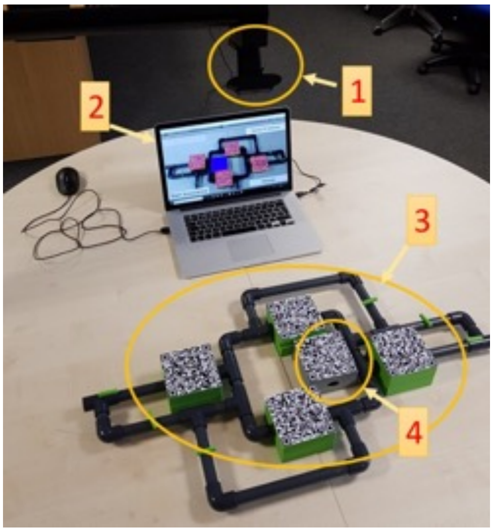
The key for improving the spatial referencing with respect to video/voice supports lies in the AR technology and the utilisation of the relative positions of the objects with respect to the anchor marker located in both the novice and the expert environments.

In order to provide a better understanding of how ARRA works, the following sections will show a practical example in sec. 5.3.1 and the technical development details in sec. 5.3.2.

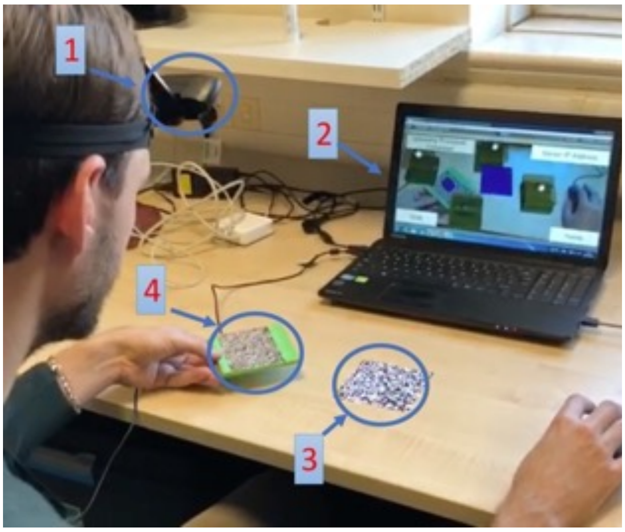
5.3.1 ARRA: a practical example

In this section a practical example of how ARRA work is reported. The pictures utilised for explaining ARRA have been taken during the validation tests and are utilised here to better explain to the reader 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 sec 5.4.1.



(a) Novice's maintenance scenario



(b) Remote Expert

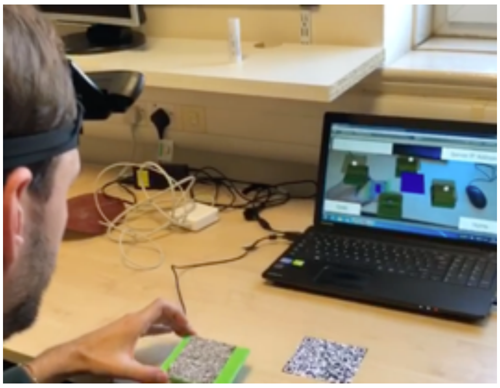
Figure 5.2 novice and expert environments when utilising ARRA

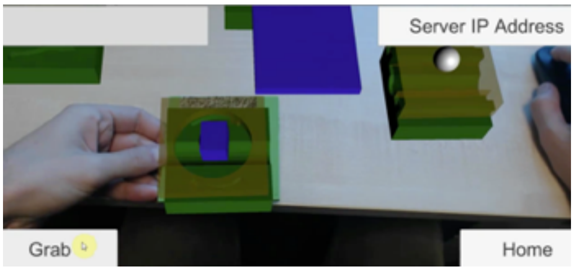
Two different environments have to be considered, for instance: the novice's shop-floor (Figure 5.2a) and the expert's desk (Figure 5.2b).

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 POV. 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.

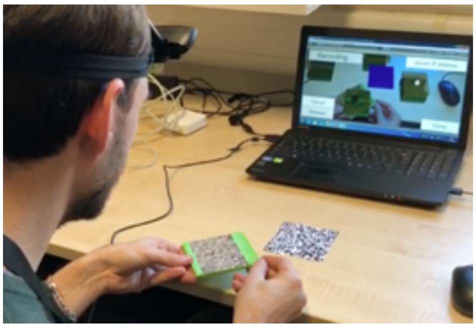
It is worth to mention that, in both environments, the RGB camera and laptop could potentially be substituted with an HMD. The description of the example will now progress following the actual operation time sequence.

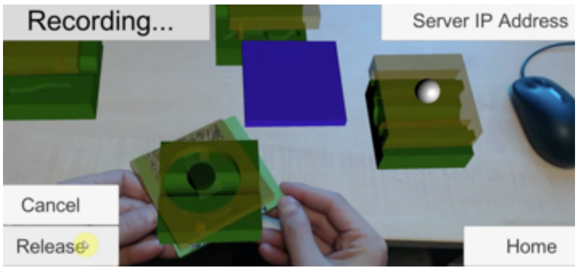




(a) request for assistance received

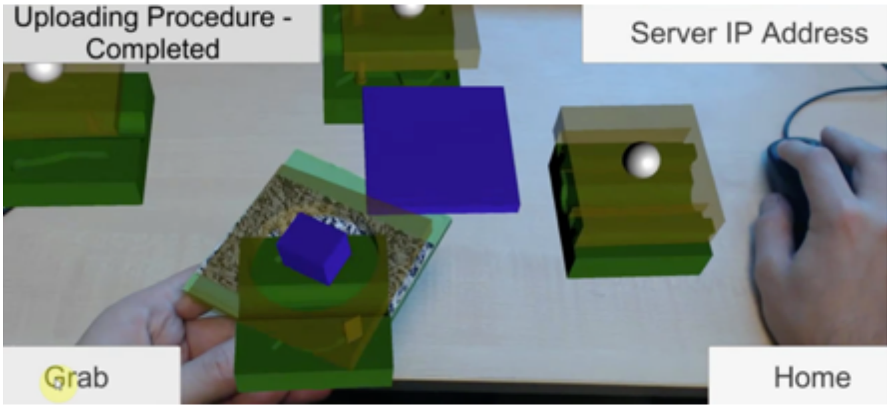
(b) grabbing virtual object





(c) manipulating virtual object

(d) releasing virtual object



(e) uploading the procedure

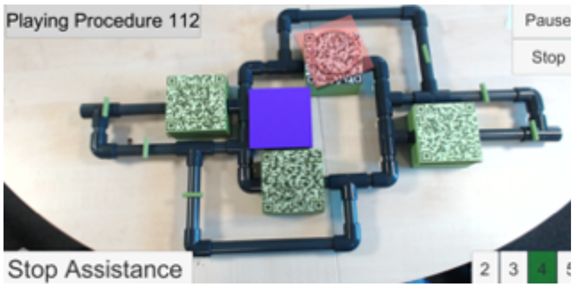
Figure 5.3 expert scenario since receiving the request for assistance

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

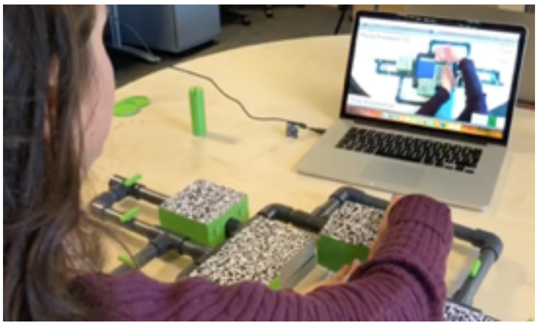
The remote expert accepts the request for assistance and visualises the CAD models of the object to be maintained. More specifically, the four objects regonised by the novice’s camera (Figure 5.2a) and their position and orientation with respect to the novice’s anchor marker, are reproduced virtually on the experts’ screen maintaining the same relative position with the maintainer’s anchor marker (Figure 5.3a). The expert understands what maintenance operation has to be carried out based on his expertise and places the virtual manipulator over the virtual component that has to be moved (Figure 5.3b). Once he/she presses “Grab” (bottom left on Figure 5.3b), the virtual component starts following the virtual manipulator movements. In Figure 5.3c and Figure 5.3d we can see respectively, the expert rotating the virtual manipulator and the virtual component rotating as well. Also, on the top left of the expert’s screen (Figure 5.3d), 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 Figure 5.3d) and the information recorded is uploaded on a cloud server db. The remote expert can now keep monitoring the movements of the real novice’s objects through the virtual components on his display.

The novice, which has been waiting for the assistant feedback (Figure 5.4a), receives the maintenance procedure.

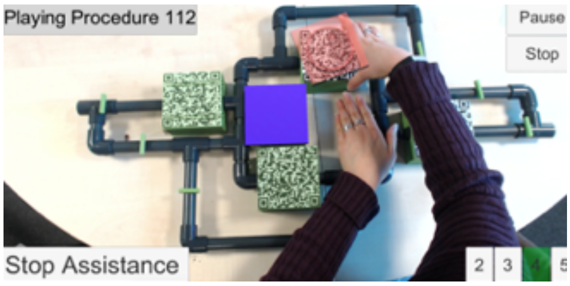
(a) requesting assistance



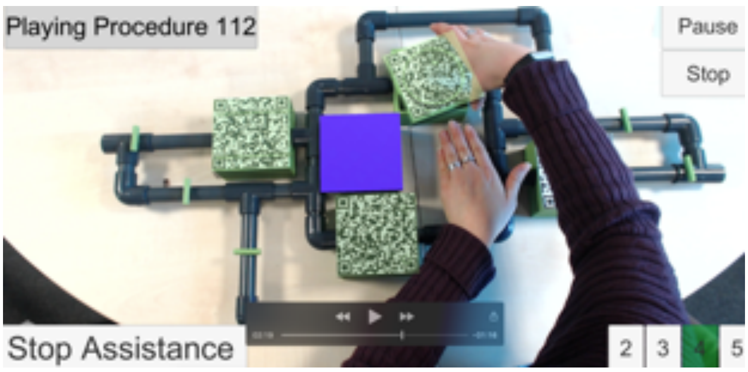
(b) receiving assistance. Virtual object becomes red and animates.



(c) preforming task as suggested by animation



(d) user interface while performing maintenance



(e) Real object becomes green when aligned with virtual object suggested position.

Figure 5.4 novice scenario since receiving the remote support through ARRA

On the top left of the novice's display, the statement "Playing Procedure x" is shown (Figure 5.4b). All the objects that are positioned and orientated correct will be overlaid with its own CAD model coloured 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 (Figure 5.3). The novice can now proceed and move the real object as indicated by the animation (Figure 5.4c). In this specific case, the component has to rotate counter-clockwise. Once the position and orientation indicated by the expert are reached by the real component, the overlaid CAD becomes green as shown in Figure 5.4e.

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/she 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 is worth to mention 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.

5.3.2 Technical Development

ARRA schematic concept (Figure 5.1) and practical example have been described in the previous sections. It is clear that ARRA approach concretises 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 5.1. The software has been developed specifically for this study and the hardware utilised in this study. The architecture utilised in this project is schematically reported in Figure 5.5 below and explained in this section.

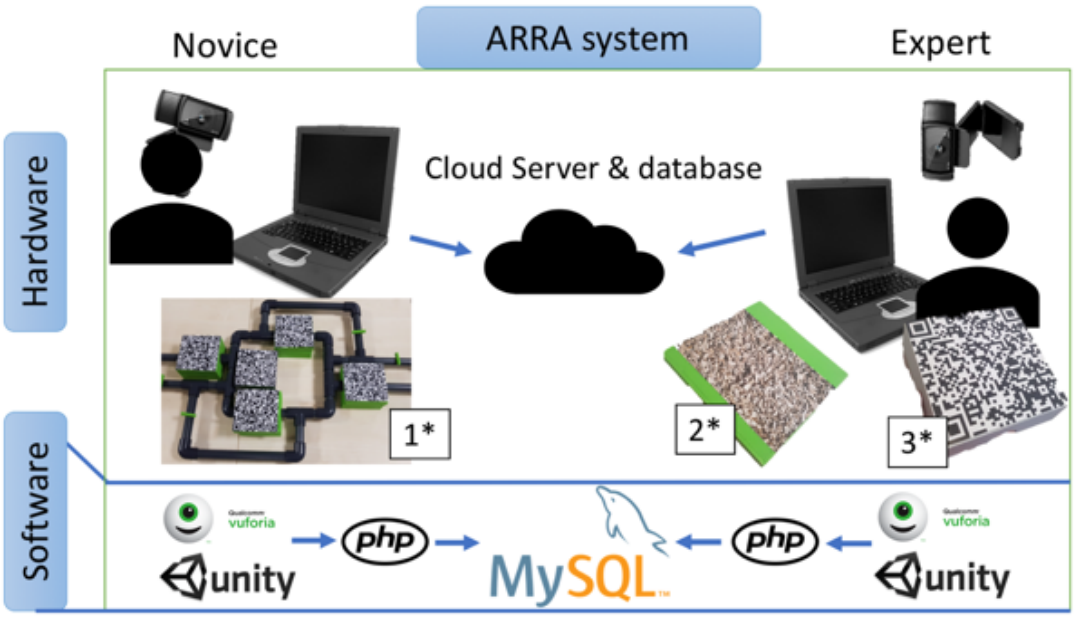


Figure 5.5 ARRA's hardware and software

Similarly, to ARRA's concept described in Figure 5.1, in Figure 5.5 the novice maintainer is on the left and the expert remote maintainer is on the right. Both of them are equipped with an RGB camera Logitech 1080, a laptop and an anchor marker (3*, also described in sec 5.3.1). 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 due to the fact that 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 Head Mounted Displays 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 focus of the study.

The software for carrying out this study has been developed in Unity 3D and takes advantage of the Vuoforia SDK for allowing the markers recognition. Rather than directly recognising the objects, in fact, the author 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 by means of AR as described in the practical example in sec 5.3.1

The server has been firstly located on a local machine by utilising XAMPP: opensource cross-platform webserver 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. In fact, only two tables of 8 columns are located on the server: 1) the Real Object DOF (RODOF), and 2) the Virtual Object DOF (VODOF). 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 really low compared to videocall 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.

In order to ensure the reproducibility of the study, Appendix 7C.2 reports the main scripts, functions and query developed by the author for ARRA.

5.4 ARRA Test Design and Methodology

ARRA has been described in sec. 5.3 both schematically and through a practical example. Among the expected benefit in the utilisation of ARRA compared to videocall support for remote maintenance, the author's intent is to validate the improvement in terms of spatial referencing.

To validate ARRA, the author 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 in 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 1 but supported through "videocall support".
3) **Comparison** between 1 and 2.

The case study and therefore the maintenance operations utilised for testing purposes are reported in sec. 4.4.1. The validation's steps 1 and 2 have been calculated utilising the test described in the following section 5.4.1. The results have then been compared (step 3) and are shown in sec 5.5

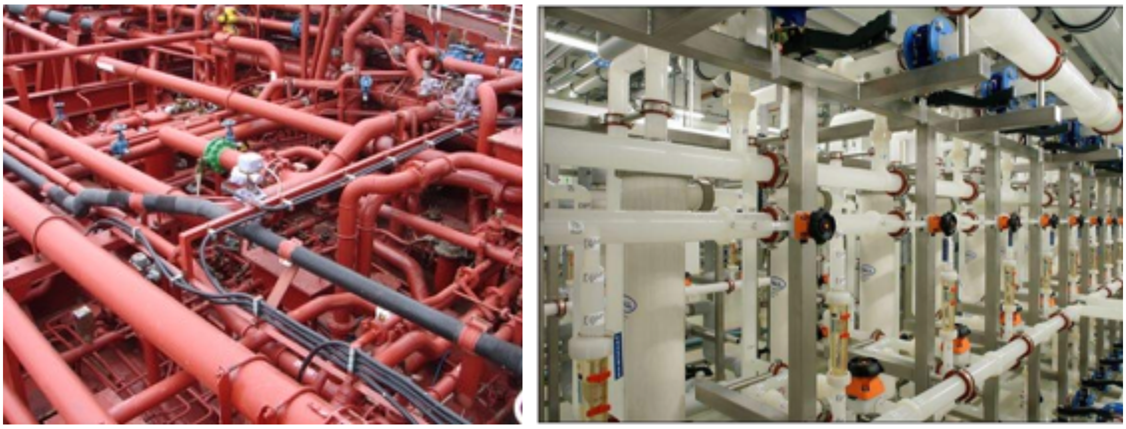
5.4.1 Validation Case Study

In this section the case study utilised for validation purposes is described. The quantitative validation process is then described in detail in sec 5.4.2.

The author decided to utilise, as a case study, an operation which 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 [84]
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 limited to.



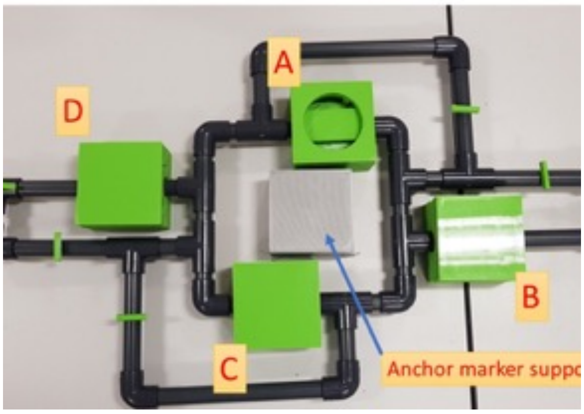
(a) piping system of a chemical tanker

(b) UPW Installation using PVDF Piping

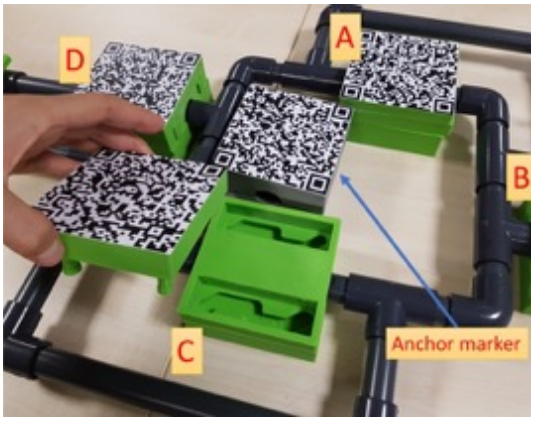
Figure 5.6 Examples of piping systems in industry.

Figure 5.6 shows two examples of piping systems in industry. On the left (a), the piping system of a chemical tanker [108], on the right (b) a UPW Installation using PVDF Piping [109].

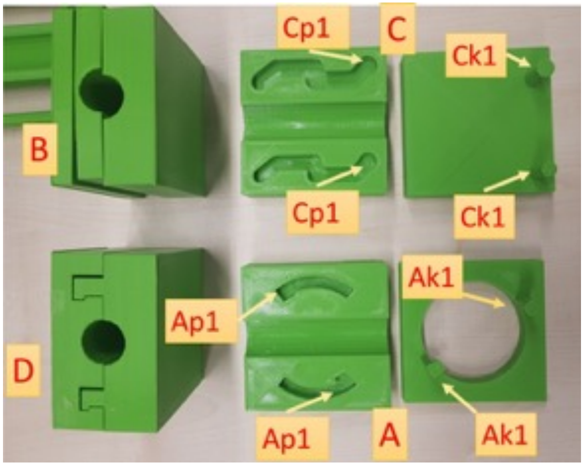
For performing ARRA's validation test and quantify the improvements in terms of spatial referencing, the mock-up shown in Figure 5.7 has been 3D printed and assembled.



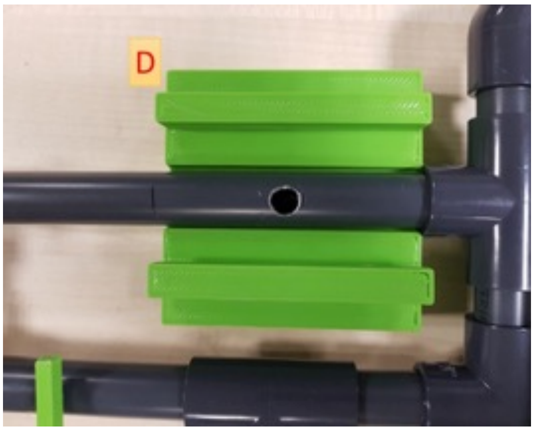
(a) top view of mock-up simulating piping



(b) lock C opened



(c) details of locks A,B, C and D



(d) lock D opened showing pipe fault

Figure 5.7 3D printed mock-up of piping system for validation purposes.

Starting from, the mock-up consists of a piping system built utilising 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 clearly 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 Figure 5.7b, the markers for allowing the objects recognition have 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 Figure 5.7c. 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 author has 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 Figure 5.7d is shown an example of 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. It has been utilised a material depositing head of 0.8mm and layers of 0.6mm.

5.4.2 Quantitative Validation Test methodology

In this section is described the method utilised for quantifying the spatial referencing errors reduction due to the utilisation of ARRA vs videocall support. Firstly, the quantification of the spatial referencing errors has been carried out separately for ARRA and videocall support utilising respectively the method schematically described in Figure 5.9 and Figure 5.9. Then the results have been statistically analysed and compared for calculating the spatial referencing reduction.

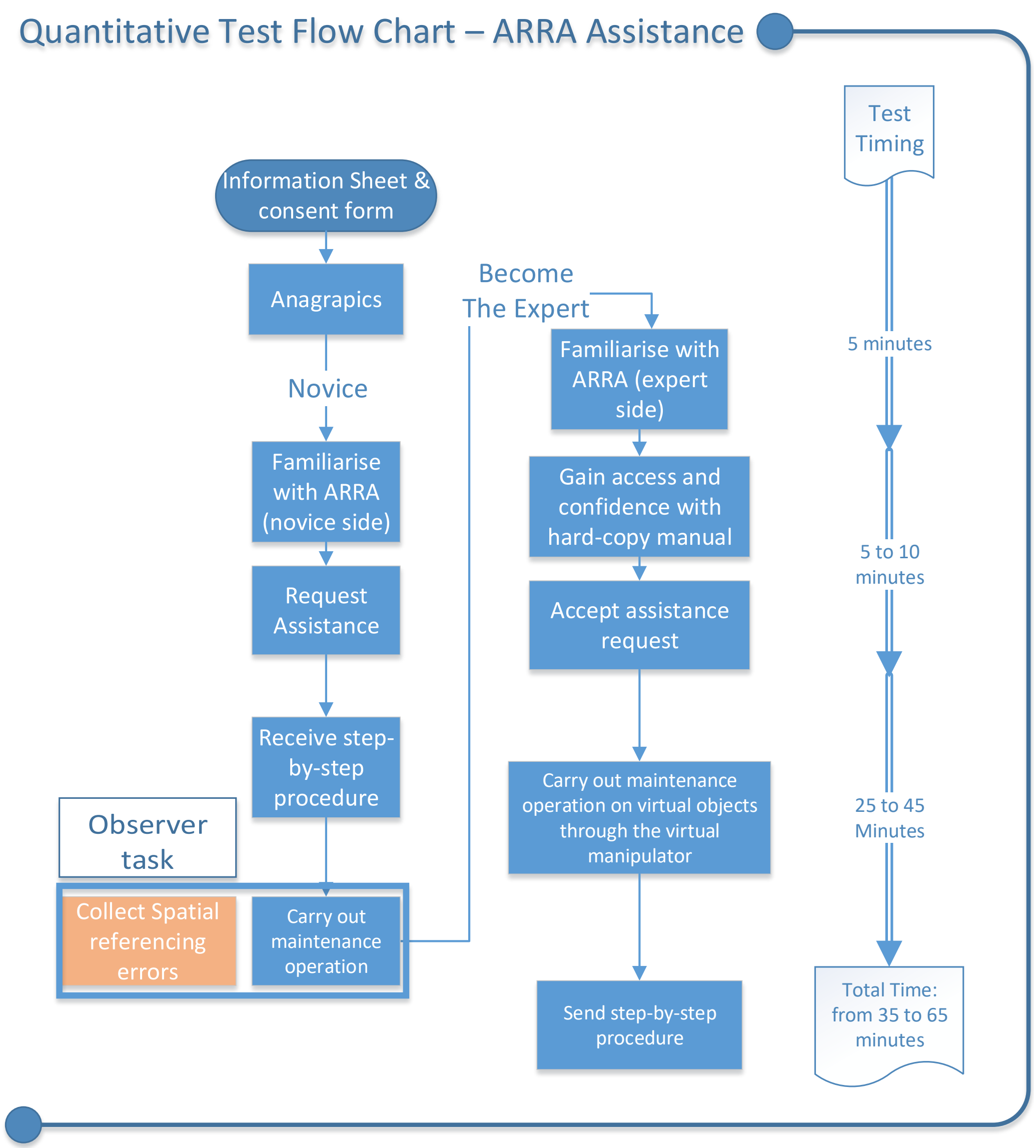


Figure 5.8 Schematic representation of spatial referencing errors quantification test for ARRA

Following the time line, on the top left, the participant is asked to read and sign the consent form as well as providing demographical data. The latter are used only for a qualitative analysis of the sample and do not affect the test results.

The participant is then identified as a "novice" and is positioned in front of the assembly to be maintained (as in Figure 5.4a) and introduced to ARRA by the observer. He/she can then request for assistance through ARRA, receive the procedure remotely built by an expert and carry out the maintenance operation.

The possible maintenance operations are 8 and consist in the 4 locks assembly and disassembly procedures.

During maintenance operations, the observer will collect the spatial referencing information (7C.1). The spatial referencing errors collected in this test can be of three kinds (see Table 5.1):

1. Wrong object identification (Error Kind: Identification)
2. Wrong object direction (Error Kind: Direction)
3. Wrong lock coupling - only applies assembly operations (Error Kind: Coupling)

The first one concretises when the participant, after receiving the procedure, puts his hands on the wrong lock. The second one happens when the component of the lock is moved towards an incorrect direction or rotated in the opposite sense. The last one consists in associating the chosen top component of a lock with the bottom component of a different lock (only applies to assembly operations).

The observer collects the data by filling a specific designed form with a fixed multiple choice. For each of the spatial errors mentioned above, in fact, the observer can also choose among two descriptors: “opposite” and “other” (see Table 5.1). Opposite is 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

Other is utilised when the participant makes a different kind of spatial referencing error.

The test is completed once the maintenance operation is carried out. The novice participant can now become the 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 through a hardcopy manual, and showing him how the remote expert interface of ARRA works, in fact, he is now able to virtually manipulate the locks as a remote expert.

The spatial errors collected have then to be compared with the one occurring when the same maintenance procedures are performed through videocall support.

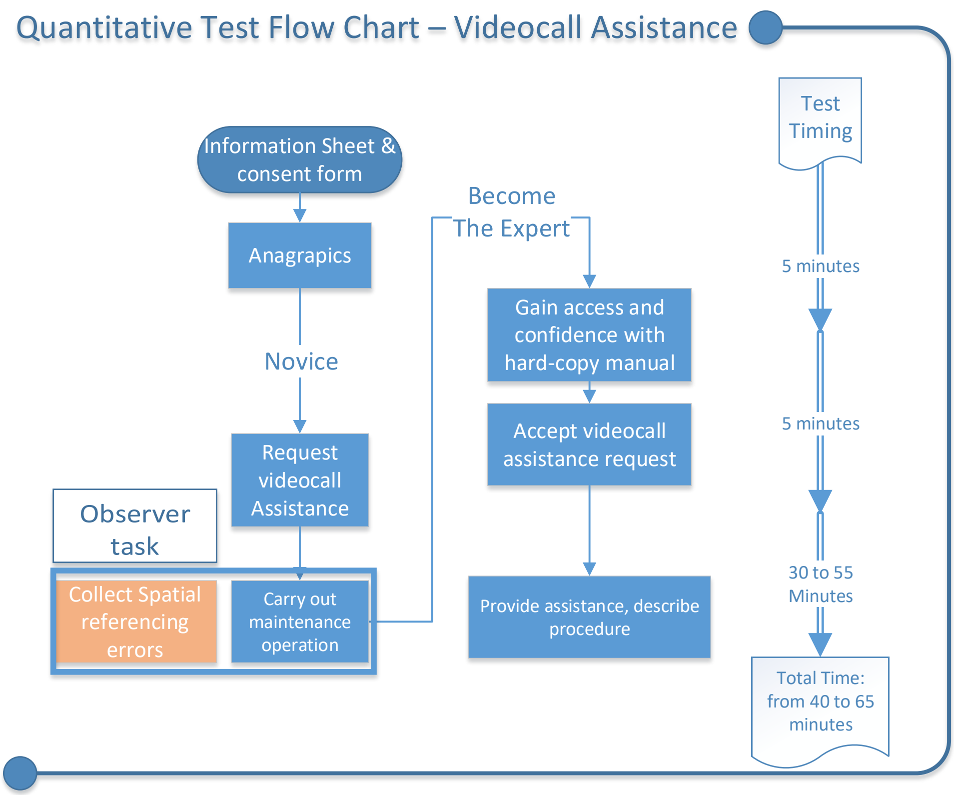


Figure 5.9 Schematic representation of spatial referencing errors quantification test for videocall

In this case a new participant is placed in front of the assembly and is provided with an RGB camera for video-calling the support. The orientation of the camera and the position of the participant with respect to the assembly are random. The randomness is eased by the utilisation of a round table as the working area. On the other side, the expert is a participant that has already done the test as a novice who, moreover, is 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 are then compared to calculate the final spatial errors reduction due to the utilisation of ARRA vs videocall support.

Table 5.1 is provided as an extract of the complete Table C.1 reporting the data collected during the tests.

Table 5.1 Extract of the complete dataset table utilised for further analysis (see page 139 for columns definitions).

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, the table presents 5 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 4 locks. The "spatial reference" and "error kind" columns report the data collected by the observer (defined in page 139). 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 sec 5.5.

5.5 ARRA Analysis and Results

This section reports the analysis and results of the test described in section 5.4. The test aimed to quantify the improvement in terms of special referencing when performing a maintenance operation remotely supported by ARRA vs videocall.

A total of 60 participants (42m/18f) took part in the 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. The average age was 27.9 (21, 33, SD=3.48). Half of them performed the maintenance operation supported by ARRA; the other half were supported by videocall. 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’s research ethics policy.

The data has been collected utilising the methodology described in sec 5.4.2 and transcribed in a dataset table whose extract has been shown in Table 5.1. The full table comprises of 450 rows and is reported in Table C.1. This number can be also calculated as reported in Equation 1:

$$\begin{aligned}&Number\ of\ Rows\\&\quad = Number\ of\ Participants\\&\quad \times\ Operations\ performed\ by\ participant\\&\quad \times\ Average\ Number\ of\ Error\ Kinds\end{aligned}$$

Equation 1. Calculation of number of rows of dataset table.

In the equation above, the number of participants is 60; the operations performed by each participant for testing purposes is 3 and the average number of error kinds is 2.5. The latter is due to the fact that, as already explained at page 139, for disassembly operations 1-4, the error kinds are 2: identification and direction.

For assembly operations 5-8, the error kinds are 3: identification, direction and coupling. Therefore, considering that each operation has been tested the same amount of times, the average is $(2 + 3)/2 \ = 5$.

For understanding whether there is or not a statistically significant association between the RA method utilised (ARRA vs videocall) and the amount of spatial referencing errors, it is required to perform a statistical test. Due to the nature of the sample, the author decided to perform the 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 videocall 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 videocall are two independent groups since the utilisation of one excludes the utilisation of the other.

The result of the Pearson's chi square test is that there is a statistically significant association between ARRA and videocall, $\chi2(2) = 72.68$, $p < 0.05$. The overall significant effect of the utilisation of ARRA considering all the operations is shown in Figure 5.10.

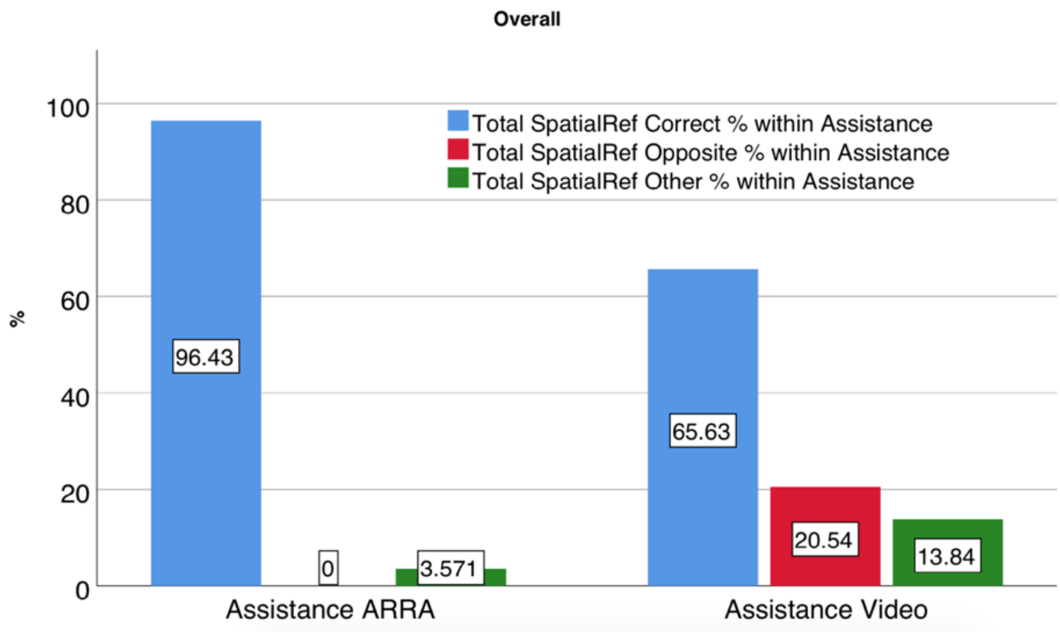


Figure 5.10 overall percentages of spatial referencing errors

Figure 5.10 shows that, when utilising ARRA, 96.43% of the tests resulted in correctly addressing the 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 videocall were performed correctly. About 20.5% of the tests resulted in presenting the spatial error defined as "opposite". 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.

For further understanding 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 Figure 5.11.

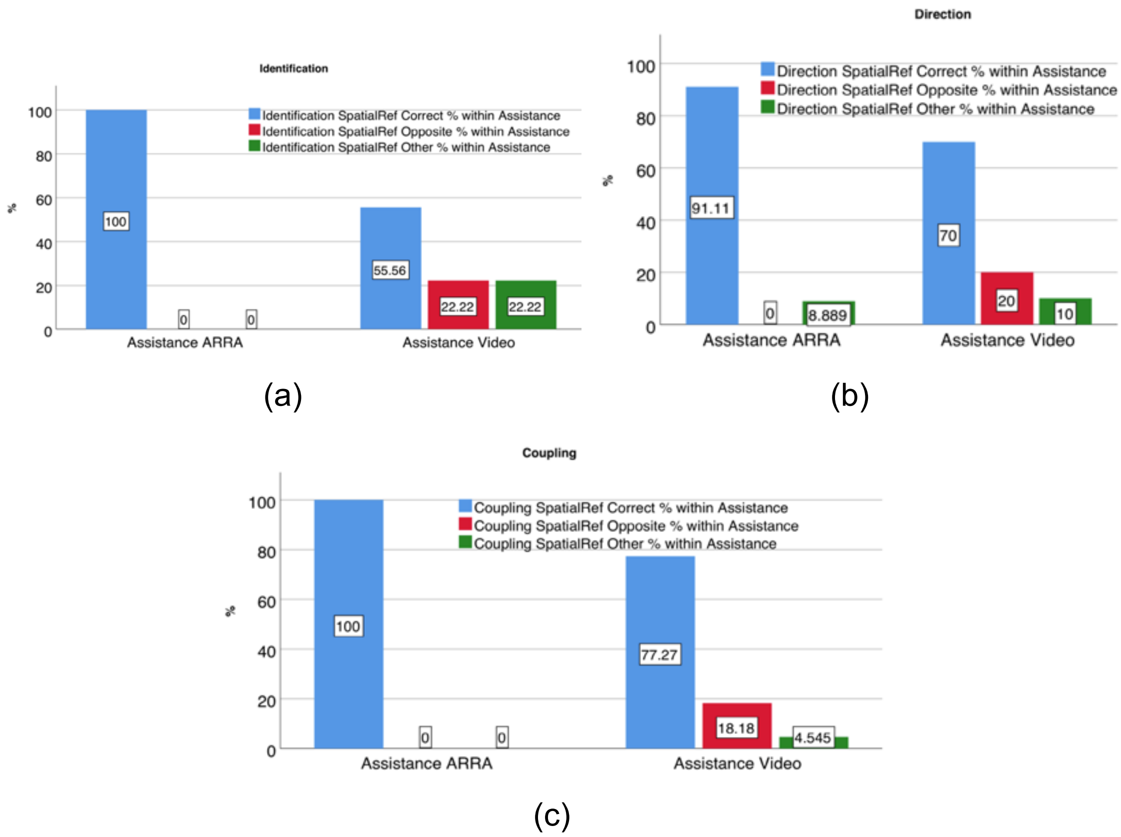
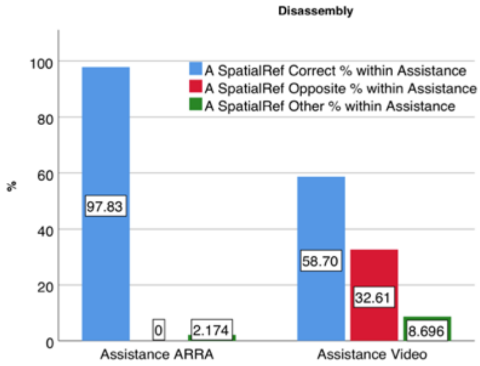


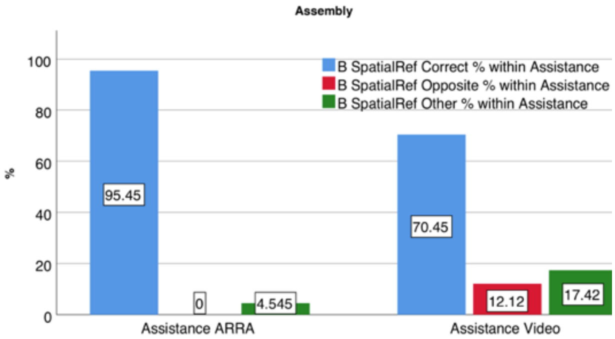
Figure 5.11 spatial referencing errors by kind: (a) identification, (b) directional and (c) coupling

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 top and bottom components of the locks. About 9% of spatial errors were made in terms of moving directions (b).

Furthermore, the author investigated if the kind of operation (assembly or disassembly) affected the spatial referencing results (Figure 5.12)



(a)



(b)

Figure 5.12 spatial referencing errors collected for disassembly and assembly operations

Even though there is not a huge difference for ARRA in supporting an assembly or a disassembly operation, we can notice that videocall support results in slightly different outcomes. More specifically, for the disassembly operations videocall 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 have been plotted separately. Figure 5.13 reports the 4 disassembly operations, Figure 5.14 reports the 4 assembly operations.

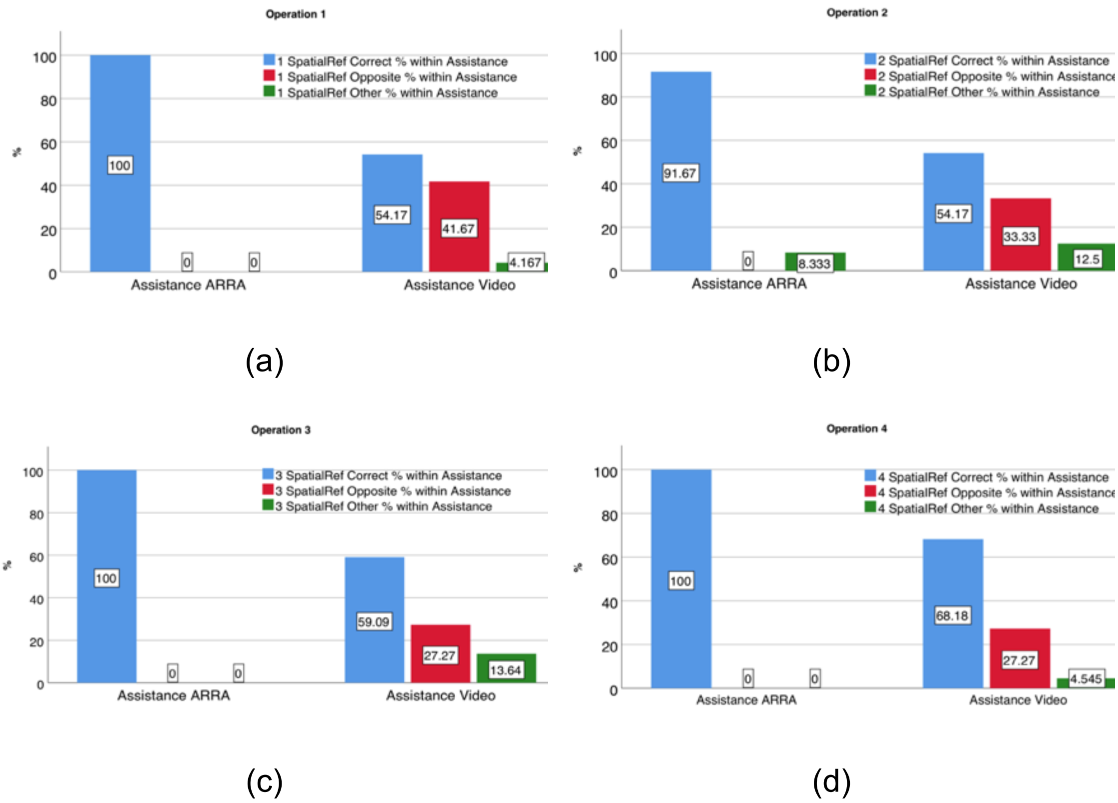


Figure 5.13 spatial referencing errors collected for each disassembly operation separately

The test which utilised ARRA for disassembly operations (1-4) resulted almost always in no spatial errors. Only operation 2 (b), in fact, presents “other” spatial errors.

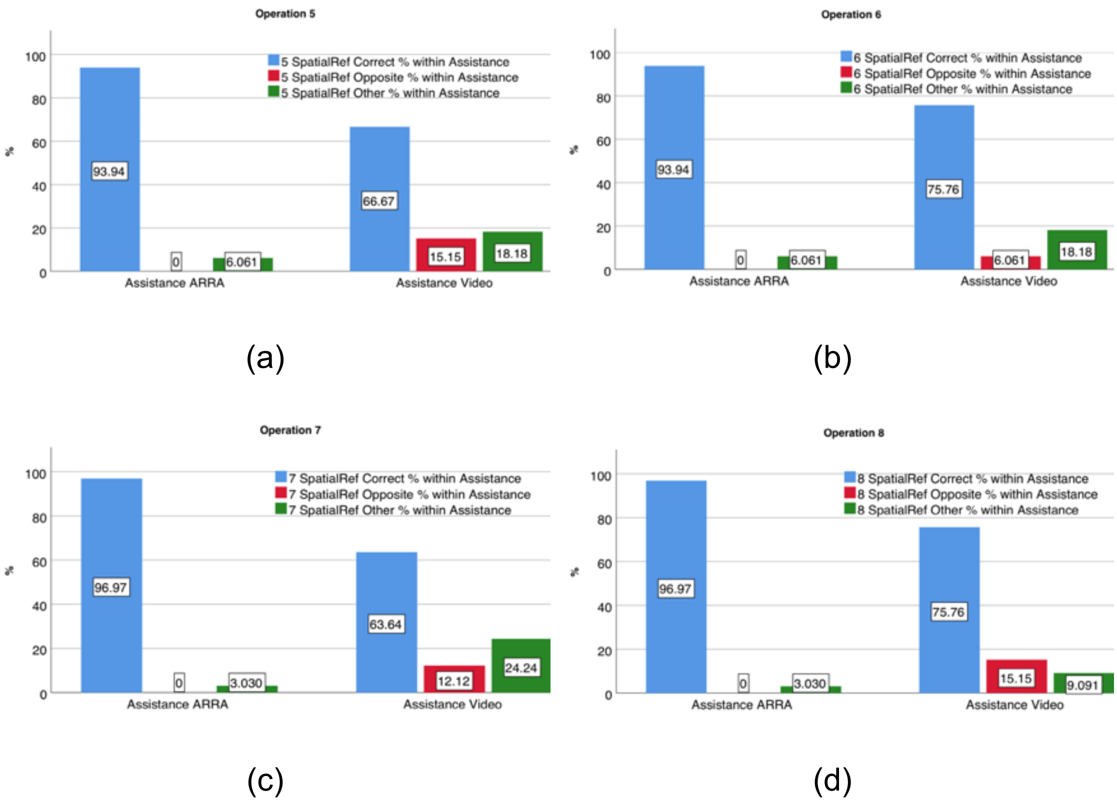


Figure 5.14 spatial referencing errors collected for each assembly operation separately

As already shown also by Figure 5.12, ARRA performed worst for disassembly operations never reaching the 100% correct spatial referencing.

5.6 ARRA Discussion

In this section the discussion about the study methodology and results is reported.

The author's intent in developing ARRA is to provide an augmented reality support for RA. Moreover, the study focuses on quantifying the improvement in terms of spatial referencing due to the utilisation of ARRA vs videocall support for maintenance.

ARRA is based on two assumptions:

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

The author considers these assumptions plausible due to the recent improvements in image processing, object tracking and recognition and hardware (processors and sensors) [84][73].

ARRA has been described in sec. 5.3 through a practical example and the technical development. Even though in this study the author has utilised some specific hardware and software solution, ARRA can be developed and implemented differently. Considering the fast advancement of the technology related with AR, in fact, 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 validation only for practical reasons. The observer of the empirical tests that have been carried out, in fact, needed to clearly understand the evolvement of each test for clearly collect the data required for assessing the spatial referencing improvements.

The study, in fact, focused also on quantifying the spatial referencing errors occurring when utilising ARRA and when utilising a videocall support for RA. The methodology utilised for the empirical tests, took inspiration from similar studies: Tang [95], Fiorentino [22], Henderson [14].

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 colour and, therefore, are difficult to be identified through voice indications or hard-copy manual. Moreover each one of the 4 locks has a different unlocking system. All together comprise of x,y and z translations and z rotation.

The tests have been planned carefully and small space has been given to subjectivity. The observer, in fact, has been provided with multiple choices forms and detailed schematic process for carrying on the tests.

The sample utilised for the test consisted of 60 participants and has been described in sec 5.5. No special requirements have been utilised for selecting the participants. No specific engineering or AR background was, in fact, required due to the test methodology design. The participants that took the test as novices did not need to know a-priori how ARRA works. Time for familiarising with ARRA and its user interface have been provided. The participants that took the test as experts, not only gained experience when performing the test as novices, but also have been given time for reading the hard-copy-manuals designed ad-hoc.

Regarding the results, ARRA performed always better than videocall support in terms of spatial referencing. This is due to the fact that AR relies on the references recognised by the software and is invariant with the orientation of the camera.

Videocall support, on the other side, relies on the communication between the expert and the novice. The reference system which is in the expert mind might be different from the novice's one. 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 Figure 5.13 and Figure 5.14), videocall support always presented a not neglectable percentage of spatial referencing errors of the kind "opposite".

Moving now to the three categories of errors: identification, direction and coupling (Figure 5.11); 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, the has been a 10% of 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 author found a plausible justification thanks to Figure 5.13b. The latter, in fact, shows that within the 4 disassembly operations, only operation "2" presented directional spatial errors when utilising ARRA. Operation "2" consist on the disassembly of the top component of lock B (see Figure 5.7a). It is done by rotating the top component around the "z" axis and is also reported in the practical example in Figure 5.4. Due to the inclination of the camera with respect to the assembly, the rotation has sometimes (10% of the times) been confused with a pulling movement and therefore resulted in a spatial referencing error.

At the current stage, the main limitation of ARRA resides on the remote expert assistance interface. Manipulating virtual objects, in fact, does not only rely on the verification of the two main assumptions of ARRA (1. robust tracking and recognition of real objects: 2. Availability of CAD models) described in sec. 5.3. It has been found essential to provide to the remote expert an haptic feedback in order to properly manipulate the virtual objects. The 3D visualisation, in fact, difficulty can substitute the weight and collision forces generated during a maintenance procedure.

5.7 ARRA Conclusions and future works

This study proposed an Augmented Reality support for Remote Assistance: ARRA. Its technical development and functionalities have been described. ARRA allows a remote expert to visualise, real time, the novices' maintenance problem and guide him through the solution. The remote expert, in fact, can build step by step procedures through the virtual manipulation of the virtual objects which replicate 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 utilises a mock-up of a piping system. The comparison has been made with remote assistance through videocall. The results have shown an overall improvement of 27% in terms of correct spatial referencing operation when utilising ARRA vs videocall. Moreover, ARRA performed perfectly when considering identification and coupling errors. The tests regarding the direction of the objects, on the other side, have shown a not neglectable percentage of errors of about 10%.

It is the author's belief that, through the utilisation of HMD and a more advanced UI, ARRA could overcome also these also directional spatial referencing errors and reach 100% of correct operations for similar assemblies.

The limitation related with the lack of haptic feedback for the expert assistant who has to manipulate the virtual objects could be addressed through a technology similar to vibrotactile bracelet utilised by Webel [30]. Future studies could compare the application of ARRA with and without the bracelet and understand the effects on the remote assistance provided. Also, different haptic devices could be developed ad-hoc for ARRA applications.

6 Overall Discussion

The discussion of the methodologies and findings of chapters 2 to 5 have been reported within each chapter and are not addressed in the current chapter.

This chapter proposes the overall discussion of the project with specific focus on linking the findings of each chapter to deliver the aim of the project and clearly show its contributions to knowledge (sec. 6.1), real-world impact (sec 6.2) and limitations (sec. 6.3).

The aim of the project is *to develop an automated geometrical-based method for creating AR contents in maintenance thus easing AR implementation in Industry.*

In order to understand what is challenging the real-wold implementation of AR in industry, the project started by investigating into the AR technology state of the art, the current practice in maintenance and the expected future developments. This has been done through a SLR which has been reported in chapter 2. The main three research gaps identified and addressed in this thesis are fully described in sec. 2.4. These are synthetised below:

1. Research gap 1: AR is fragmented in terms of hardware, development platforms, programming language, software and user interface. There is a need for a methodology for selecting AR technology for maintenance. This thesis has proposed IPSAR in chapter 3.
2. Research gap 2: The process for creating digital contents for AR in maintenance requires several professional figures and is mostly manual (Figure 2.22) and time consuming. The experts refer to this problem as "contents-related issues". This thesis proposes FARP in chapter 4.
3. Research gap 3: One of the less studied field of applications has been found to be Remote Maintenance (only 8% in Figure 2.3). AR has not exploited his potential in remote applications. The quantification of the advantages in terms of spatial referencing has not been addressed by previous studies. This thesis proposes ARRA in chapter 5.

Carrying out the SLR for clearly understanding the technological gaps that are preventing the wide utilisation of AR in supporting Maintenance has been an essential step for putting the bases of this project and a valuable reference for researchers approaching AR and aiming to *ease the implementation of AR in maintenance through the utilisation of an automated geometrical-based method.*

6.1 Contributions to knowledge

This section describes the contributions to knowledge that the author has created by carrying out the SLR and then addressing three main gaps identified in it and summarised in the previous section.

The first major contribution resides in the SLR, chapter 2. The SLR of Augmented Reality (AR) applications in Maintenance has provided a detailed insight of the current state of the art and future developments.

The SLR has been carried out following a rigorous methodology explained in the chapter. It makes the study fully reproducible and objective.

It is based on the articles published between the 1997 and 2017 in the field of AR and AR in Maintenance. Starting from 723 publications, 30 articles have been selected to be analysed for providing the results of the SLR. Moreover other 47 articles have been referenced to explain and validate the results.

It is a valuable article for anyone who is exploring AR and AR in Maintenance for the first time. It not only shows what are the current applications, but also categorises them by field of application, maintenance applications and technologies utilised. Each one of these is explained in detail and the main research gaps are reported.

It differs from other review articles thanks to the strictly systematic approach utilised.

The second major contribution is IPSAR, proposed in chapter 3. In this chapter, the author has addressed *research gap 1* by developing and proposing a process for selecting AR technology for maintenance.

The process described has been developed based on a bibliographic study and through a systematic annotation of the correlation between technological choices vs maintenance application. It concretises in a questionnaire which can potentially be answered by a non-AR expert. The output of the questionnaire are the AR technological choices in terms of hardware, development platform and visualisation method system that should be made for a specific maintenance scenario.

IPSAR is a valuable tool for any industry or academic approaching AR. It can be used for having a preliminary understanding of the technology required for a specific research or industrial application.

The third major contribution is FARP, proposed in chapter 4. In this chapter, the author has addressed *research gap 2* (contents creation) found in the SLR (chapter 2) by developing and testing FARP: Fast Augmented Reality Programming.

FARP is a geometrical based method which attempts to capture the expert maintainer's knowledge, store it and make it accessible to novice maintainers in a step-by-step AR procedure format. FARP is based on the assumptions that the objects in FOV are recognised by the AR system and that the CAD models of all the components involved in the maintenance procedure are available. FARP records the geomatical positions and orientations of each object in space and, through the processes described in sec. 4.3.2, transforms the data into knowledge by creating the AR step-by-step procedure.

The strength of FARP is that very little cognitive effort and training are required to the expert maintainer for creating the contents for AR. Moreover, FARP takes advantage of the human expertise and does not rely on computer calculated maintenance procedures which would not consider unpredicted events.

The author strongly believes in this approach for *easing the implementation of AR in industry* since it would not require training several professional figures for creating AR contents. Moreover, the potential of the approach is exciting. Potentially, in fact, if a relevant number of expert maintainers would utilise FARP, thousands of maintenance procedures could be stored and accessible for many different novices from many industries. For instance, if all the maintainers repairing different car engines would be recording their operations through FARP, any novice could be able to access the specific maintenance procedure for the specific engine selected and performing it by following the step-by-step procedure.

The last and fourth major contribution is ARRA, proposed in chapter 5. In this chapter, the author has addressed the *research gap 2* (remote assistance) found in the SLR (chapter 2) by developing and testing ARRA: Augmented Reality for Remote Assistance.

ARRA is an AR based remote assistance tool designed for improving spatial referencing within the communication between an expert maintainer and a remote novice maintainer. It has been developed starting from FARP geometrical based method and has been tested on remote assistance applications.

ARRA overcomes the spatial referencing issues that occur when a remote maintainer facing an issue calls the assistance utilising a video call. Beside the language and communication barriers such as different nomenclature of components or *"ways of explaining the problem/solution"*, in fact, it is difficult for the on-site maintainer and remote assistance to understand each other's spatial references. Of course, the problem is more emphasised when the components to be maintained are complex and present geometrical symmetries and colour homogeneities. By overlaying the digital contents of the remote expert over the novice real world, the spatial referencing issue almost disappears, and the novice is able to operate under the expert supervision throughout the full procedure. Moreover, the remote expert can produce the AR-step-by-step procedure by manipulating virtual objects which are positioned in the same relative position with each other's as seen by the novice maintainer requiring assistance.

6.2 Real-World Impact

This section describes the real-world impact that the three contributions to knowledge created throughout this project could have.

Regarding the IPSAR, the author believes that this sort of tool could impact the real world by increasing the awareness of AR industries and let maintainers approach the technology with a clear suggested path in terms of technological investment and therefore, professional figures required. This attempt to ease the choices that have to be made by industries should positively affect their confidence thus *ease AR implementation in industry.*

Regarding FARP, the author believes that the impact it could have on the real world includes:

1. Capturing the expert’s knowledge in digital format. Storing the geometrical data involved in the operations is essential for improving designs and improving training.

2. Provide simplified training to novices maintainers. Having access to AR step-by-step procedures, in fact, would not require them to be trained on the specific case but a general “good practice training” on the specific topic (e.g. hydraulic systems, pneumatic systems, electronic systems…) and a “safety training” could be sufficient.

3. Improve employees' flexibility. Potentially every maintainer should be able to carry out any operation by following the step-by-step procedures. Industry could save training costs and reduce the number of maintainers required to be operational anytime for corrective maintenance.

4. Reduce maintenance cost. This is related no only to point 3, but also to the potential improvements in terms of time savings and errors reductions that AR and FARP have been proven to be capable of.

Regarding ARRA, the author believes that the impact it could have on the real world includes:

1. Decrease not-operational condition of industrial machineries by providing prompt and effective remote assistance.
2. Increase customer satisfaction by efficiently providing assistance on industrial, but also consumers goods.
3. Reduce travelling costs involved in requiring experts and vendors assistance

Having discussed the impact of each separate piece of work of this project, it is now interesting to discuss the overall impact of the project on the real world. A good way of doing so is by carrying out a Value Proposition Analysis (VPA) which shows the fit between the technology developed and the customer (sponsor) requirements by answering a number of questions raised.

In Figure 6.1, the customer has compiled the “customer profile” section and the author of this work has compiled the “Value Map”. All the values inserted by the author in the value map have been described throughout the document and, in most of the cases, proven by empirical testing. By reading through the VPA, it seems clear that AR technology and, more specifically this project outcomes, respond to a number of needs of the customer.

The customer, in this case, is a company in the automotive industry. It has identified a number of real-world problems (*Pains*) that need to be overcome in order to improve the *Gains* and carry out the *Jobs*. On the other side, the author has proven that the AR technology developed and tested within this project is potentially able to provide the *Pain Relievers*, *Gain Creators* and *Product and Services* reported in the Value Map therefore achieving the fit between this project and the customer profile

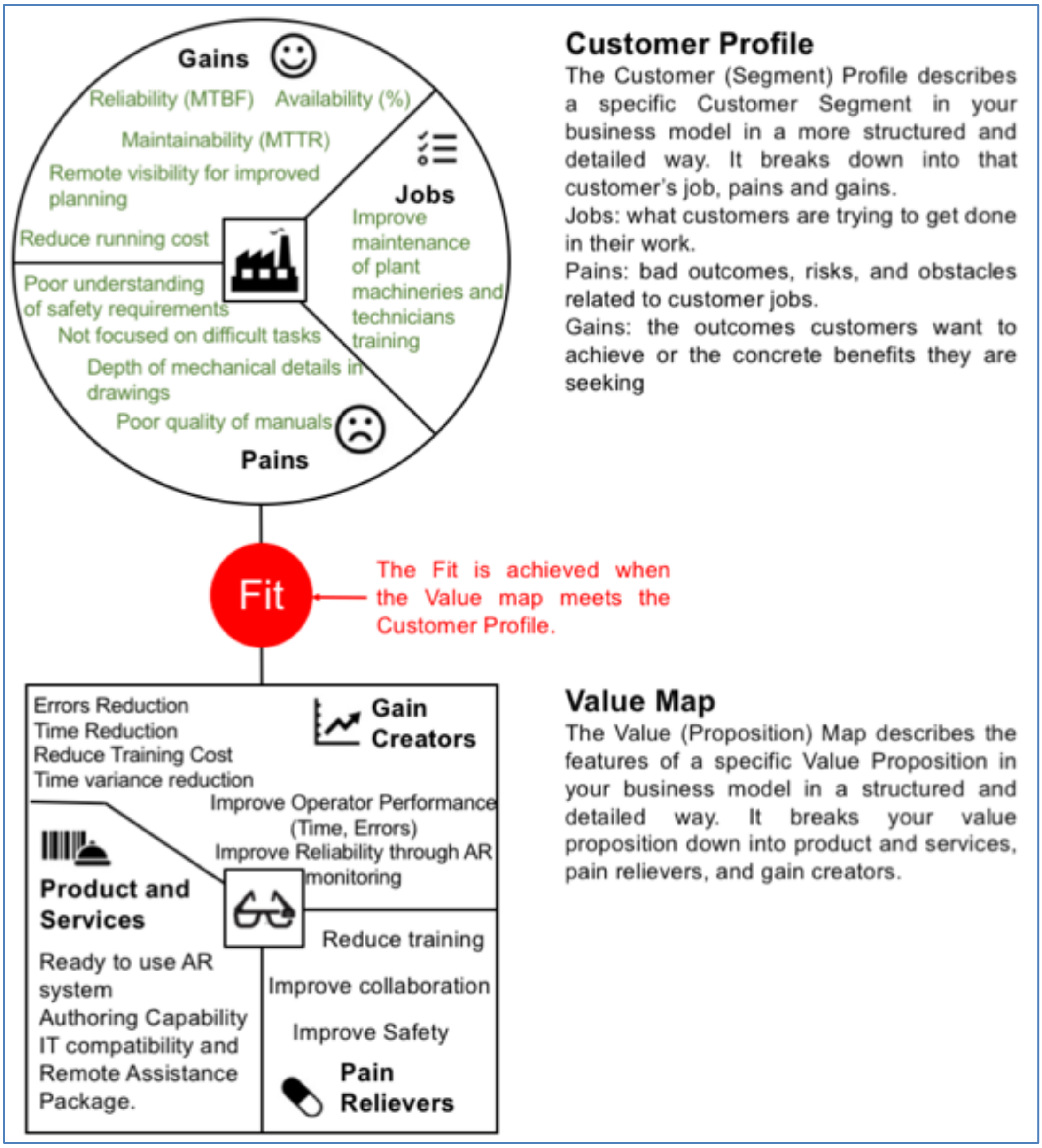


Figure 6.1 Value Proposition Analysis – Customer Vs AR Value Map.

More specifically, looking at the Value Map (bottom of Figure 6.1) IPSAR helps developing a ready to use AR system and address the IT compatibility at an early stage of the AR system design.

FARP improves the operator performance (time, errors), reduces training and provides authoring capabilities therefore addressing (see customer profile on Figure 6.1):

1. *industrial pains*: poor understanding of safety requirements, poor quality of manuals
2. *gains*: reducing running cost
3. jobs: improve maintenance of plant machineries and technicians training

Finally, ARRA improves collaboration by providing a ready to use AR system for remote assistance with authoring capabilities addressing (see customer profile on Figure 6.1) specifically:

1. *industrial pains*: poor quality of manuals and depth of mechanical details in drawings
2. *gains*: reducing running cost and remote visibility
3. *jobs*: improve *maintenance of plant machineries and technicians training*

Therefore, the author believes there is a fit between AR and the methods developed within this project and the industrial requirements shown in the value map.

6.3 Limitations

This section reports the limitations of the overall project and the three methods developed within it: IPSAR, FARP and ARRA. Discussions have been provided for each method (IPSAR, FARP and ARRA) separately (see sec. 3.5, 4.6 and 5.6). These cover the limitations of each method. Still, there are some general considerations which can be done for the overall project.

The SLR has been carried out focused on the technological aspects of AR in the maintenance and manufacturing fields. The SRL has been used to put the basis of this research which, as consequence, is limited to manufacturing and maintenance. Other fields of applications such as entertainment, teaching, medical or tourism have not been addressed in this project. Still, it is the author belief that the method developed could be transferred to other research field after appropriate re-design.

Even though the author tried to propose methods which do not rely on the current technology, disruptive advancements in AR technology could lead to the devaluation of the contributions to knowledge created in this research. More specifically, AI could provide in a not-so-near future an alternative solution for the selection of AR technologies for maintenance as well as the creation and management of the AR contents.

The authoring method proposed FARP (for on-situ maintenance) and ARRA (for remote maintenance), both are based on two main assumptions:

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

Even though the author believes these to be reasonable assumptions for the near future, still these assumptions limit the utilisation of AR in industry today. AR systems which utilise RGB cameras are not able to recognise and track the objects in the FOV robustly and reliably. Systems which utilise infrared cameras need a controlled environment and tedious set-up. Fortunately, it is well-known, that emerging depth cameras could be providing the solution to this technological problem which is currently affecting AR. On the other side, regarding the availability of CAD models, the author believes the assumption to be acceptable due to the increasing utilisation of digital engineering for supporting manufacturing. Therefore, this assumption can be considered reasonable, especially for the manufacturing and maintenance fields which are the fields of interest of this research project.

Finally, it is worth to mention that this project does not cover the economic aspects involved in the development and management of an AR system. Even though it is necessary for Industry to understand the Return On Investment (ROI) involved in the utilisation of a new technology, the author considered this aspect out of this project’s scope. Only technological aspects have been considered in this thesis.

7 Overall Conclusions and Future Works

The work has provided an investigation into AR applications in maintenance and proposed solutions for overcoming three of the main gaps found in literature which are preventing the wide and effective implementation of AR in the real-wold of maintenance.

Each academic gap and proposed solution have been described in detail throughout this document and the objectives set in section 1.1.1 (Figure 1.2) have been achieved.

The work outcomes are:

1. A clear understanding of the state of the art of AR in maintenance and the identification of areas of improvements. This has been achieved through a SLR described in chapter 2. Currently AR applications in maintenance have shown great potential in improving human performances in terms of time and errors reductions, safety and, in general, lowering the cognitive load. The areas of improvement encompass hardware, development platforms, tracking and authoring capabilities.

2. A questionnaire-based process for selecting AR for specific maintenance operations have been developed (chapter 3) based on the bibliographic study. This tool allows non-AR experts to understand what hardware, development platform and visualisation method should be utilised for supporting the specific maintenance task selected with AR.

3. FARP has been developed and tested as a solution for providing authoring capabilities to maintainers. FARP method avoids the need of several professional figures (engineers, CAD modellers, animators and programmers) for creating AR contents for maintenance and delivering step-by-step AR procedures. Moreover, the AR procedures created are based on the expert maintainer experience therefore consider the human factor and real-maintenance scenario which, not always, is known to the author of the maintenance manuals. FARP has been

empirically tested. The results have shown that the procedures created through FARP are as efficient as the one found in literature since the advantages in terms of time saving and errors reductions are comparable. More specifically, an overall 35,8% of time reduction and 68.6 errors reduction have been appreciated on the case study utilised. The advantage of FARP with respect to the literature studies is that it requires little effort to author the AR contents for maintenance.

4. ARRA has been developed and tested as a solution for providing Remote Assistance through AR focusing on improving the spatial awareness. ARRA allows a novice maintainer to ask for assistance to a remote expert who does not have the real object to be maintained in his environment. ARRA allows the remote expert to manipulate the virtual replicas of the real novice's environment and build the step-by-step AR procedure. The novice will than visualise the procedure overlaid on his real object that need maintenance. The improvement in spatial referencing has been tested and quantified against video-call maintenance support. An overall improvement of 27% has been appreciated in identifying the correct objects, coupling the correct components and operating towards the correct directions within the case study utilised for this work. A non-neglectable 8.9% of errors has been appreciated regarding operating towards the correct direction alone. Still this percentage is lower than video-call maintenance support directional errors (avg.10%) shown in Figure 5.11b.

The author believes that the sum of these 4 main contributions provides a step-forward in *easing the implementation of AR in maintenance*.

Specific future works suggestions have been made by the author in each chapter (see sec. 2.4, 3.5, 4.7 and 5.7). Still there are some general future works suggestions that can be made for the overall project.

Researchers approaching AR authoring for maintenance should look into the utilisation of Machine Learning and Artificial Intelligence for automating the process of gathering human experiences and utilise it for authoring purposes.

The author believes, in fact, that the full potential of AR can be reached only by the effective application of intelligent learning algorithms and therefore this project put the bases for support such advancements (see . 4.7).

The synergic integration of intelligent learning and automated creation of digital manuals for maintenance could be explored. Researchers should focus on the information gathered from the real maintenance scenarios in order to build a set of instructions which are not only based on the manufacturers experience but also on the real final customer utilisation. The documentation provided with equipment, in fact, not always satisfies the industrial needs therefore increasing trainings requirements and maintenance costs.

In general, as soon as the technology will allow robust and reliable objects recognition, AR authoring research projects should get rid of mock-ups and validate on real scenarios in order to divulgate data captured on the real maintenance field. Even though in this project the author simulated real working environments, in fact, AR still is applied on humans and therefore needs full proof of being safe and effective before being implemented. Current HMD, for instance, reduce the FOV of technicians and therefore might not be accepted in industrial shop floors.

Future studies should also address the utilisation of AR technology on loose and flexible components such as wiring and hoses. Even if the object recognition and tracking become robust and reliable, this kind of components do not have a standard configuration (including position and orientation). Researcher could try to address the issue by modelling the connections/terminals or develop an ad-hoc recognition system based on materials and surface properties. The development and utilisation of portable interferometers could help in addressing this issue.

Researchers approaching AR under the hardware point of view should aim to design HMD which do not reduce the FOV of the technicians and that can be considered ergonomically acceptable. Current HMD are heavy and significantly increase the volume of the technician’s head. These are not suitable for real shop-floor activities.

Researchers approaching AR applications for remote assistance should consider the remote virtual object manipulation as a smart solution for intuitively transfer information to remote operators thus reducing travelling costs. In order to enhance the manipulation of virtual objects, it has been found necessary to further investigate into the utilisation of haptic devices such as the vibro-bracelet utilised by Webel [30]. Ideally, the haptic device, should reproduce the gravitational and collision loads involved in any maintenance operation.

REFERENCES

[1] R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi, "A systematic review of augmented reality applications in maintenance," *Robotics and Computer-Integrated Manufacturing*. 2018.

[2] S. K. Ong, M. L. Yuan, and A. Y. C. Nee, "Augmented reality applications in manufacturing: A survey," *Int. J. Prod. Res.*, vol. 46, no. 10, pp. 2707–2742, 2008.

[3] I. Fernández del Amo, J. A. Erkoyuncu, R. Roy, R. Palmarini, and D. Onoufriou, "A systematic review of Augmented Reality content-related techniques for knowledge transfer in maintenance applications," *Comput. Ind.*, vol. 103, pp. 47–71, 2018.

[4] P. Milgramt and F. Kishinott, "Special Issue on Networked Reality," *IEICE Trans. Inf. Syst.*, vol. E77–D, no. 12, pp. 1321–1329, 1994.

[5] R. Azuma, R. Behringer, S. Feiner, S. Julier, and B. Macintyre, "Recent Advances in Augmented Reality," *IEEE Comput. Graph. Appl.*, vol. 2011, no. December, pp. 1–27, 2001.

[6] G. Westerfield, A. Mitrovic, and M. Billinghurst, "Intelligent augmented reality training for motherboard assembly," *Int. J. Artif. Intell. Educ.*, vol. 25, no. 1, pp. 157–172, 2015.

[7] M. E. C. Santos, J. Polvi, T. Taketomi, G. Yamamoto, C. Sandor, and H. Kato, "Toward Standard Usability Questionnaires for Handheld Augmented Reality," *IEEE Comput. Graph. Appl.*, vol. 35, no. 5, pp. 66–75, 2015.

[8] K. Komonen, "A cost model of industrial maintenance for pro " tability analysis and benchmarking," *Int. J. Prod. Econ.*, vol. 79, pp. 15–31, 2002.

[9] A. C. C. dos Santos, M. E. Delamaro, and F. L. S. Nunes, "The Relationship between Requirements Engineering and Virtual Reality Systems: A Systematic Literature Review," *2013 XV Symp. Virtual Augment. Real.*, pp. 53–62, 2013.

[10] F. Pearson, *Systematic approaches to a successful literature review*, vol. 30, no. 2. 2014.

[11] B. Kitchenham, O. Pearl Brereton, D. Budgen, M. Turner, J. Bailey, and S. Linkman, "Systematic literature reviews in software engineering - A systematic literature review," *Inf. Softw. Technol.*, vol. 51, no. 1, pp. 7–15, 2009.

[12] F. Zhou, H. B. L. Dun, and M. Billinghurst, "Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR," *Proc. - 7th IEEE Int. Symp. Mix. Augment. Real. 2008, ISMAR 2008*, pp. 193–202, 2008.

[13] Y. Shen, S. K. Ong, and A. Y. C. Nee, "Augmented reality for collaborative product design and development," *Des. Stud.*, vol. 31, no. 2, pp. 118–145, 2010.

[14] S. Henderson and S. Feiner, "Exploring the benefits of augmented reality documentation for maintenance and repair," *IEEE Trans. Vis. Comput. Graph.*, vol. 17, no. 10, pp. 1355–1368, 2011.

[15] R. Grasset, A. Dünser, and M. Billinghurst, "The design of a mixed-reality book: Is it still a real book?," *Proc. - 7th IEEE Int. Symp. Mix. Augment. Real. 2008, ISMAR 2008*, vol. 6, no. 4, pp. 99–102, 2008.

[16] C. F. Lindberg, S. Tan, J. Yan, and F. Starfelt, "Key Performance Indicators Improve Industrial Performance," *Energy Procedia*, vol. 75, pp. 1785–1790, 2015.

[17] C. Koch, M. Neges, M. König, and M. Abramovici, "Natural markers for augmented reality-based indoor navigation and facility maintenance," *Autom. Constr.*, vol. 48, pp. 18–30, 2014.

[18] F. De Crescenzio, M. Fantini, F. Persiani, L. Di Stefano, P. Azzari, and S. Salti, "Augmented reality for aircraft maintenance training and operations support," *IEEE Comput. Graph. Appl.*, 2011.

[19] H. Álvarez, I. Aguinaga, and D. Borro, “Providing guidance for maintenance operations using automatic markerless augmented reality system,” *2011 10th IEEE Int. Symp. Mix. Augment. Reality, ISMAR 2011*, pp. 181–190, 2011.

[20] H. Ramirez, E. G. Mendivil, P. R. Flores, and M. C. Gonzalez, “Authoring software for augmented reality applications for the use of maintenance and training process,” *Procedia Comput. Sci.*, vol. 25, pp. 189–193, 2013.

[21] J. Zhu, S. K. Ong, and A. Y. C. Nee, “A context-aware augmented reality system to assist the maintenance operators,” *Int. J. Interact. Des. Manuf.*, vol. 8, no. 4, pp. 293–304, 2014.

[22] M. Fiorentino, A. E. Uva, M. Gattullo, S. Debernardis, and G. Monno, “Augmented reality on large screen for interactive maintenance instructions,” *Comput. Ind.*, vol. 65, no. 2, pp. 270–278, 2014.

[23] M. Neges, C. Koch, M. König, and M. Abramovici, “Combining visual natural markers and IMU for improved AR based indoor navigation,” *Adv. Eng. Informatics*, vol. 31, pp. 18–31, 2017.

[24] D. Tatić and B. Tešić, “The application of augmented reality technologies for the improvement of occupational safety in an industrial environment,” *Comput. Ind.*, vol. 85, pp. 1–10, 2017.

[25] A. Sanna, F. Manuri, F. Lamberti, G. Paravati, and P. Pezzolla, “Using handheld devices to sup port augmented reality-based maintenance and assembly tasks,” *2015 IEEE Int. Conf. Consum. Electron. ICCE 2015*, pp. 178–179, 2015.

[26] C. Nakajima and N. Itho, “A support system for maintenance training by augmented reality,” *Proc. - 12th Int. Conf. Image Anal. Process. ICIAP 2003*, pp. 158–163, 2003.

[27] N. Zenati-Henda, A. Bellarbi, S. Benbelkacem, and M. Belhocine, “Augmented reality system based on hand gestures for remote maintenance,” in *International Conference on Multimedia Computing and*

Systems -Proceedings, 2014, vol. 0, pp. 5–8.

[28] S. J. Henderson and S. Feiner, “Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret,” *Sci. Technol. Proc. - IEEE 2009 Int. Symp. Mix. Augment. Reality, ISMAR 2009*, pp. 135–144, 2009.

[29] S. J. Henderson and S. K. Feiner, “Augmented Reality for Maintenance and Repair (ARMAR),” *Distribution*, p. 62, 2007.

[30] S. Webel, U. Bockholt, T. Engelke, N. Gavish, M. Olbrich, and C. Preusche, “An augmented reality training platform for assembly and maintenance skills,” *Rob. Auton. Syst.*, vol. 61, no. 4, pp. 398–403, 2013.

[31] F. Lamberti, F. Manuri, A. Sanna, G. Paravati, P. Pezzolla, and P. Montuschi, “Challenges, opportunities, and future trends of emerging techniques for augmented reality-based maintenance,” *IEEE Trans. Emerg. Top. Comput.*, vol. 2, no. 4, pp. 411–421, 2014.

[32] T. H. C. Chiang, S. J. H. Yang, and G. J. Hwang, “An augmented reality-based mobile learning system to improve students’ learning achievements and motivations in natural science inquiry activities,” *Educ. Technol. Soc.*, vol. 17, no. 4, pp. 352–365, 2014.

[33] J.-Y. Didier *et al.*, “AMRA : Augmented Reality Assistance in Train Maintenance Tasks,” *4th ACM/IEEE Int. Symp. Mix. Augment. Real. - Work. Ind. Augment. Real.*, pp. 1–10, 2005.

[34] S. Zhao, Y. Zhang, B. Zhou, and D. Ma, “Research on gesture recognition of augmented reality maintenance guiding system based on improved SVM,” *7th Int. Symp. Adv. Opt. Manuf. Test. Technol. Opt. Test Meas. Technol. Equip.*, vol. 9282, p. 92822L, 2014.

[35] T. Engelke, J. Keil, P. Rojtberg, F. Wientapper, S. Webel, and U. Bockholt, “Content first - A concept for industrial augmented reality maintenance applications using mobile devices,” *2013 IEEE Int. Symp. Mix. Augment. Reality, ISMAR 2013*, pp. 251–252, 2013.

[36] T. Haritos and N. D. Macchiarella, “A mobile application of augmented reality for aerospace maintenance training,” *AIAA/IEEE Digit. Avion. Syst. Conf. - Proc.*, vol. 1, pp. 1–9, 2005.

[37] T. Wójcicki, “Supporting the diagnostics and the maintenance of technical devices with augmented reality,” *Diagnostyka*, vol. 15, no. 1, pp. 43–47, 2014.

[38] V. Havard, D. Baudry, A. Louis, and B. Mazari, “Augmented reality maintenance demonstrator and associated modelling,” in *2015 IEEE Virtual Reality Conference, VR 2015 - Proceedings*, 2015, pp. 329–330.

[39] J. Wang, Y. Feng, C. Zeng, and S. Li, “An augmented reality based system for remote collaborative maintenance instruction of complex products,” *IEEE Int. Conf. Autom. Sci. Eng.*, vol. 2014–Janua, pp. 309–314, 2014.

[40] M. Hincapié, A. Caponio, H. Rios, and E. González Mendívil, “An introduction to Augmented Reality with applications in aeronautical maintenance,” *Int. Conf. Transparent Opt. Networks*, pp. 1–4, 2011.

[41] S. Goose, S. Sudarsky, X. Zhang, and N. Navab, “Speech-enabled augmented reality supporting mobile industrial maintenance,” *IEEE Pervasive Comput.*, vol. 2, no. 1, pp. 65–70, 2003.

[42] A. H. Behzadan and V. R. Kamat, “Interactive Augmented Reality Visualization for Improved Damage Prevention and Maintenance of Underground Infrastructure,” *Constr. Res. Congr. 2009*, pp. 1214–1222, 2009.

[43] G. Klinker, O. Creighton, A. H. Dutoit, R. Kobylinski, C. Vilsmeier, and B. Brügge, “Augmented maintenance of powerplants: A prototyping case study of a mobile AR system,” *Proc. - IEEE ACM Int. Symp. Augment. Reality, ISAR 2001*, pp. 124–133, 2001.

[44] T. Nakagawa, T. Sano, and Y. Nakatani, “Plant maintenance support system by augmented reality,” *IEEE SMC’99 Conf. Proceedings. 1999 IEEE Int. Conf. Syst. Man, Cybern. (Cat. No.99CH37028)*, vol. 1, pp. 768–

773, 1999.

[45] N. S. Lakshmprabha, P. Mousouliotis, L. Petrou, S. Kasderidis, and O. Beltramello, “Augmented reality for maintenance application on a mobile platform,” *Virtual Real. (VR), 2015 IEEE*, pp. 355–356, 2015.

[46] A. Y. C. Nee, S. K. Ong, G. Chryssolouris, and D. Mourtzis, “Augmented reality applications in design and manufacturing,” *CIRP Ann. - Manuf. Technol.*, vol. 61, no. 2, pp. 657–679, 2012.

[47] G. Dini and M. D. Mura, “Application of Augmented Reality Techniques in Through-life Engineering Services,” *Procedia CIRP*, vol. 38, pp. 14–23, 2015.

[48] S. G. Lee, Y. S. Ma, G. L. Thimm, and J. Verstraeten, “Product lifecycle management in aviation maintenance, repair and overhaul,” *Comput. Ind.*, vol. 59, no. 2–3, pp. 296–303, 2008.

[49] S. You and M. Krage, “Overview of remote diagnosis and maintenance for automotive systems,” *2005 SAE World Congr.*, no. 724, pp. 1–8, 2005.

[50] G. Reinhart and C. Patron, “Integrating augmented reality in the assembly domain - Fundamentals, benefits and applications,” *CIRP Ann. - Manuf. Technol.*, vol. 52, no. 1, pp. 5–8, 2003.

[51] M. L. Yuan, S. K. Ong, and A. Y. C. Nee, “Augmented reality for assembly guidance using a virtual interactive tool,” *Int. J. Prod. Res.*, vol. 46, no. 7, pp. 1745–1767, 2008.

[52] H. Martínez, T. Fabry, S. Laukkanen, J. Mattila, and L. Tabourot, “Augmented reality aiding collimator exchange at the LHC,” *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 763, no. 2014, pp. 354–363, 2014.

[53] A. Liverani, G. Amati, and G. Caligiana, “Interactive control of manufacturing assemblies with Mixed Reality,” *Integr. Comput. Aided. Eng.*, vol. 13, no. 2, pp. 163–172, 2006.

[54] S. Bottecchia, “TAC: Télé-assistance Collaborative, Réalité augmentée et NTIC au service des experts et des opérateurs dans le cadre d’un tpache de maintenance industrielle supervisée,” 2010.

[55] E. Weiss, G. Gehlen, S. Lukas, C. H. Rokitansky, and B. Walke, “MYCAREVENT- Vehicular communication gateway for car maintenance and remote diagnosis,” *Proc. - Int. Symp. Comput. Commun.*, pp. 318–322, 2006.

[56] M. A. Taie, M. Diab, and M. Elhelw, “Remote prognosis, diagnosis and maintenance for automotive architecture based on least squares support vector machine and multiple classifiers,” *Int. Congr. Ultra Mod. Telecommun. Control Syst. Work.*, pp. 128–134, 2012.

[57] X. Wang, P. E. D. Love, M. J. Kim, and W. Wang, “Mutual awareness in collaborative design: An Augmented Reality integrated telepresence system,” *Comput. Ind.*, vol. 65, no. 2, pp. 314–324, 2014.

[58] V. Chimienti, S. Iliano, M. Dassisti, G. Dini, and F. Failli, “Guidelines for implementing augmented reality procedures in assisting assembly operations,” *IFIP Adv. Inf. Commun. Technol.*, vol. 315, pp. 174–179, 2010.

[59] X. Wang, S. K. Ong, and A. Y. C. Nee, “Real-virtual components interaction for assembly simulation and planning,” *Robot. Comput. Integr. Manuf.*, vol. 41, pp. 102–114, 2016.

[60] S. Takata *et al.*, “Maintenance: Changing role in life cycle management,” *CIRP Ann. - Manuf. Technol.*, vol. 53, no. 2, pp. 643–655, 2004.

[61] H. Regenbrecht, G. Baratoff, and W. Wilke, “Augmented reality projects in the automotive and aerospace industries,” *IEEE Comput. Graph. Appl.*, vol. 25, no. 6, pp. 48–56, 2005.

[62] X. Wang, P. S. Dunston, and M. Skiniewski, “Mixed Reality Technology Applications in Construction Equipment Operator Training,” *21st Int. Symp. Autom. Robot. Constr.*, no. October 2016, 2004.

[63] U. Neumann and A. Majoros, “Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance,” *Proceedings. IEEE 1998 Virtual Real. Annu. Int. Symp. (Cat. No.98CB36180)*, pp. 4–11, 1998.

[64] N. Navab, “Developing killer apps for industrial augmented reality,” *IEEE Comput. Graph. Appl.*, vol. 24, no. 3, pp. 16–20, 2004.

[65] B. Kress and T. Starner, “A review of head-mounted displays (HMD) technologies and applications for consumer electronics,” *SPIE Proc.*, vol. 8720, p. 87200A, 2013.

[66] J. P. Rolland and H. Fuchs, “Optical Versus Video See-Through Head-Mounted Displays in Medical Visualization,” *Presence Teleoperators Virtual Environ.*, vol. 9, no. 3, pp. 287–309, 2000.

[67] G. Schall *et al.*, “Handheld Augmented Reality for underground infrastructure visualization,” *Pers. Ubiquitous Comput.*, vol. 13, no. 4, pp. 281–291, 2009.

[68] D. Stanimirovic, N. Damasky, S. Webel, D. Koriath, A. Spillner, and D. Kurz, “A Mobile Augmented reality system to assist auto mechanics,” *ISMAR 2014 - IEEE Int. Symp. Mix. Augment. Real. - Sci. Technol. 2014, Proc.*, no. September, pp. 305–306, 2014.

[69] J. Carmigniani, B. Furht, M. Anisetti, P. Ceravolo, E. Damiani, and M. Ivkovic, “Augmented reality technologies, systems and applications,” *Multimed. Tools Appl.*, vol. 51, no. 1, pp. 341–377, 2011.

[70] Y. D. Kim and I. Y. Moon, “e-Training content delivery networking system for augmented reality car maintenance training application,” *Int. J. Multimed. Ubiquitous Eng.*, vol. 8, no. 2, pp. 69–80, 2013.

[71] A. Olwal, J. Gustafsson, and C. Lindfors, “Spatial augmented reality on industrial CNC-machines,” *Proc. SPIE*, vol. 6804, no. 1, p. 680409, 2008.

[72] S. Siltanen, *Theory and applications of marker-based augmented reality*.

2012.

[73] L. Yu, S. K. Ong, and A. Y. C. Nee, “A tracking solution for mobile augmented reality based on sensor-aided marker-less tracking and panoramic mapping,” *Multimed. Tools Appl.*, vol. 75, no. 6, pp. 3199–3220, 2016.

[74] M. E. C. Santos, A. Chen, T. Taketomi, G. Yamamoto, J. Miyazaki, and H. Kato, “Augmented reality learning experiences: Survey of prototype design and evaluation,” *IEEE Trans. Learn. Technol.*, vol. 7, no. 1, pp. 38–56, 2014.

[75] T. Langlotz, S. Mooslechner, S. Zollmann, C. Degendorfer, G. Reitmayr, and D. Schmalstieg, “Sketching up the world: In situ authoring for mobile Augmented Reality,” *Pers. Ubiquitous Comput.*, vol. 16, no. 6, pp. 623–630, 2012.

[76] H. Bae, J. White, M. Golparvar-Fard, Y. Pan, and Y. Sun, “Fast and scalable 3D cyber-physical modeling for high-precision mobile augmented reality systems,” *Pers. Ubiquitous Comput.*, vol. 19, no. 8, pp. 1275–1294, 2015.

[77] T. Jung, M. D. Gross, and E. Y.-L. Do, “Annotating and sketching on 3D web models,” *Int. Conf. Intell. User Interfaces*, vol. 1, no. 206, pp. 95–102, 2002.

[78] J. A. Erkoyuncu, I. F. del Amo, M. Dalle Mura, R. Roy, and G. Dini, “Improving efficiency of industrial maintenance with context aware adaptive authoring in augmented reality,” *CIRP Annals Manufacturing Technology*, vol. 66. Accepted, January 2017, pp. 465–468, 2017.

[79] R. Palmarini, J. A. Erkoyuncu, and R. Roy, “An Innovative Process to Select Augmented Reality (AR) Technology for Maintenance,” *Procedia CIRP*, vol. 59, no. TESConf 2016, pp. 23–28, 2017.

[80] M. Fiorentino, A. E. Uva, M. Gattullo, S. Debernardis, and G. Monno, “Augmented reality on large screen for interactive maintenance

instructions," *Comput. Ind.*, 2014.

[81] M. Hincapié, A. Caponio, H. Rios, and E. González Mendívil, "An introduction to Augmented Reality with applications in aeronautical maintenance," in *International Conference on Transparent Optical Networks*, 2011.

[82] S. Webel, U. Bockholt, T. Engelke, N. Gavish, M. Olbrich, and C. Preusche, "An augmented reality training platform for assembly and maintenance skills," *Rob. Auton. Syst.*, 2013.

[83] M. Abramovici, M. Wolf, S. Adwernat, and M. Neges, "Context-aware Maintenance Support for Augmented Reality Assistance and Synchronous Multi-user Collaboration," *Procedia CIRP*, vol. 59, pp. 18–22, 2017.

[84] R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi, "A systematic review of augmented reality applications in maintenance," *Robot. Comput. Integr. Manuf.*, vol. 49, no. February, pp. 215–228, Feb. 2018.

[85] G. Csurka, M. Kraus, R. S. Laramee, P. Richard, and J. B. Eds, *Computer Vision , Imaging and Computer Graphics*, no. February. 2012.

[86] C. Knopfle, J. Weidenhausen, L. Chauvigne, and I. Stock, "Template based authoring for AR based service scenarios," *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 237–240, 2005.

[87] J. Choi, Y. Kim, M. Lee, G. J. Kim, Y. Nam, and Y. Kwon, "K-MART: Authoring tool for mixed reality contents," *9th IEEE Int. Symp. Mix. Augment. Real. 2010 Sci. Technol. ISMAR 2010 - Proc.*, pp. 219–220, 2010.

[88] A. Roth, "The Arlab and Cave libraries: On authoring augmented reality and virtual reality experiences using a graphical programming language," *2011 IEEE Int. Symp. Mix. Augment. Real. - Arts, Media, Humanit. ISMAR-AMH 2011*, pp. 101–102, 2011.

[89] J. Shim, M. Kong, Y. Yang, J. Seo, and T.-D. Han, “Interactive features based augmented reality authoring tool,” *2014 IEEE Int. Conf. Consum. Electron.*, pp. 47–50, 2014.

[90] Y. Yang, J. Shim, S. Chae, and T. D. Han, “Interactive Augmented Reality Authoring System using mobile device as input method,” *2016 IEEE Int. Conf. Syst. Man, Cybern. SMC 2016 - Conf. Proc.*, pp. 1429–1432, 2017.

[91] S. J. Henderson and S. K. Feiner, “Augmented reality in the psychomotor phase of a procedural task,” *2011 10th IEEE Int. Symp. Mix. Augment. Reality, ISMAR 2011*, pp. 191–200, 2011.

[92] R. De Amicis, A. Ceruti, D. Francia, L. Frizziero, and B. Simões, “Augmented Reality for virtual user manual,” *Int. J. Interact. Des. Manuf.*, vol. 12, no. 2, pp. 689–697, 2017.

[93] G. Csurka, M. Kraus, R. S. Laramee, P. Richard, and J. Braz, “Computer Vision, Imaging and Computer Graphics. Theory and Application: 7th International Joint Conference, VISIGRAPP 2012, Rome, Italy, February 24-26, 2012, Revised Selected Papers,” *Commun. Comput. Inf. Sci.*, vol. 359 CCIS, no. May, p. 38241, 2013.

[94] S. Lee and Ö. Akin, “Augmented reality-based computational fieldwork support for equipment operations and maintenance,” *Autom. Constr.*, vol. 20, no. 4, pp. 338–352, 2011.

[95] A. Tang, C. Owen, F. Biocca, and W. Mou, “Experimental evaluation of augmented reality in object assembly task,” *Proc. - Int. Symp. Mix. Augment. Reality, ISMAR 2002*, no. 1, pp. 265–266, 2002.

[96] S. Henderson and S. Feiner, “Opportunistic tangible user interfaces for augmented reality,” *IEEE Trans. Vis. Comput. Graph.*, vol. 16, no. 1, pp. 4–16, 2010.

[97] R. Masoni *et al.*, “Supporting Remote Maintenance in Industry 4.0 through Augmented Reality,” *Procedia Manuf.*, vol. 11, no. June, pp. 1296–1302, 2017.

[98] R. T. Azuma, “A Survey of Augmented Reality,” *Presence Teleoperators Virtual Environ.*, vol. 4, no. August, pp. 355–385, 1997.

[99] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre, “Recent advances in augmented reality,” *IEEE Comput. Graph. Appl.*, 2001.

[100] M. Dalle, G. Dini, and F. Failli, “An integrated environment based on augmented reality and sensing device for manual assembly workstations,” *Procedia CIRP*, vol. 41, pp. 340–345, 2016.

[101] T. Goldschwendt, C. Anthes, G. Schubert, D. Kranzlmuller, and F. Petzold, “HoloCollab : A Shared Virtual Platform for Physical Assembly Training using Spatially-Aware Head-Mounted Displays,” *ISMAR 2014 - IEEE Int. Symp. Mix. Augment. Real. - Sci. Technol. 2014, Proc.*, pp. 337–338, 2014.

[102] O. Oda, C. Elvezio, M. Sukan, S. Feiner, and B. Tversky, “Virtual Replicas for Remote Assistance in Virtual and Augmented Reality,” *Proc. 28th Annu. ACM Symp. User Interface Softw. Technol. - UIST ’15*, pp. 405–415, 2015.

[103] D. W. F. van Krevelen and R. Poelman, “A Survey of Augmented Reality Technologies, Applications and Limittions,” *Int. J. Virtual Real.*, 2010.

[104] R. T. Azuma *et al.*, “An Easy to Use Augmented Reality Authoring Tool for Use in Examination Purpose,” *CIRP Ann. - Manuf. Technol.*, vol. 25, no. 1, pp. 1–27, Jan. 2015.

[105] M. Bordegoni, F. Ferrise, E. Carrabba, M. Di Donato, M. Fiorentino, and A. E. Uva, “An Application Based on Augmented Reality and Mobile Technology to Support Remote Maintenance,” *EuroVR 2014 - Conf. Exhib. Eur. Assoc. Virtual Augment. Real.*, 2014.

[106] A. L. Cologni, L. Fasanotti, E. Dovere, F. Previdi, S. Bonfanti, and F. C. Owen, “Smartphone based video-telemetry logger for remote maintenance services,” *IFAC-PapersOnLine*, vol. 28, no. 3, pp. 822–827, 2015.

[107] D. Mourtzis, A. Vlachou, and V. Zogopoulos, “Cloud-Based Augmented

Reality Remote Maintenance Through Shop-Floor Monitoring: A Product-Service System Approach," *J. Manuf. Sci. Eng.*, vol. 139, no. 6, p. 061011, 2017.

[108] Wikikart99, "Piping system on a chemical tanker," 2009. [Online]. Available: https://commons.wikimedia.org/wiki/File:A_UPW_Installation_using_PVDF_Piping.png. [Accessed: 27-Jul-2018].

[109] H. Cozanet, "A UPW Installation using PVDF Piping," 2006. [Online]. Available: https://commons.wikimedia.org/wiki/File:Piping_system_on_a_chemical_tanker.jpg. [Accessed: 27-Jul-2018].

APPENDICES

Appendix A

This appendix reports the presentation showing the maintenance case scenarios designed for IPSAR validation. Each participant has been provided with the details of 5 case scenarios and the tables for reporting their choices in terms of AR need, Hardware, Development Platform and Visualisation method (see sec. 3.4)

Selecting AR Validation - Method

Method: The validation of the process for selecting AR for maintenance is made by comparing the non-experts AR questionnaire results with the AR experts choices regarding the same case study.

Note:

The same information are provided to AR experts and AR non-experts regarding the case studies. These include:

1. "Who" is doing the maintenance operation (background and training)
2. "What" is the maintenance operation (complexity and occurrence)
3. "Where" is the maintenance carried out (environmental conditions)

Selecting AR Validation– Case Studies

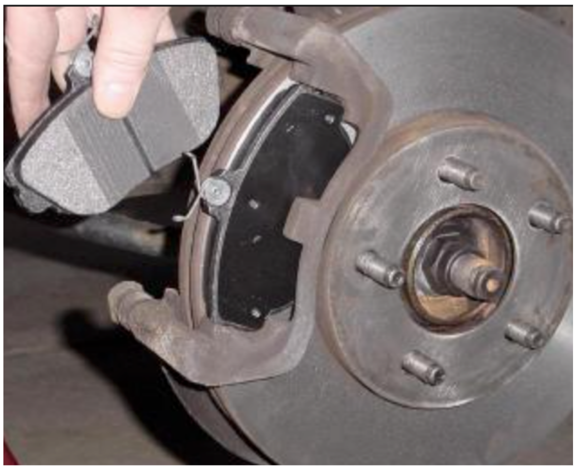
Case Study **1**

Non-expert/You have to change the car brakes pads in the garage.

Who: non-expert mechanic with little self-thought training and little maintenance experience.

What: Changing car brakes pads. It requires to remove few components. The non-expert has done it only once 5 years before.

Where: it is carried out in a properly equipped garage (tools and light).



Selecting AR Validation - Categories

AR or not AR?

- AR not recommended
- AR application for this specific application might not provide any performance improvement or is technically limited
- AR strongly recommended

Hardware?

- HMD
- Micro Projector
- Small tablet
- Large tablet
- Display
- Spatial Display
- Projector

Development Platform?

- Low level programming language
- High level programming language
- High level programming language + ad hoc "programming libraries"
- Hardware SDK
- Commercial AR developing platform

Interaction method?

- All Audio and Video contents, both static and dynamic. Remote communication
- All Audio and Video contents, both static and dynamic
- CAD(static), images, text and audio
- Images, Text and Audio
- Text and Audio
- Only text

4 Select One or Two boxes for each category.

Selecting AR Validation– Case Studies

Case study **2**

Expert mechanic has to change a car brakes pads in the garage.

Who: expert mechanic with 10 years experience in Car maintenance. Trained on the job.

What: Changing car brakes pads. It requires to remove few components and is carried out almost every day by the mechanic.

Where: it is carried out in a properly equipped garage (tools and light).

Selecting AR Validation - Categories

AR or not AR?

- AR not recommended
- AR application for this specific application might not provide any performance improvement or is technically limited
- AR strongly recommended

Hardware?

- HMD
- Micro Projector
- Small tablet
- Large tablet
- Display
- Spatial Display
- Projector

Development Platform?

- Low level programming language
- High level programming language
- High level programming language + ad hoc “programming libraries”
- Hardware SDK
- Commercial AR developing platform

Interaction method?

- All Audio and Video contents, both static and dynamic. Remote communication
- All Audio and Video contents, both static and dynamic
- CAD(static), images, text and audio
- Images, Text and Audio
- Text and Audio
- Only text

6 Select One or Two boxes for each category.

Selecting AR Validation– Case Studies

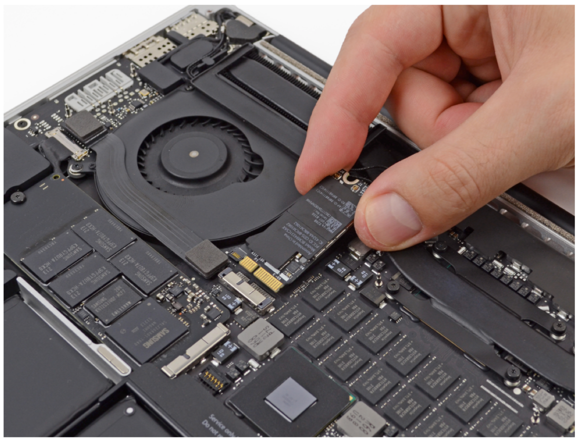
Case Study **3**

Expert Windows IT technician has to change graphic board on a Apple MAC machine

Who: 5 years experience in IT and hardware replacement. No training on MAC machines.

What: Changing car graphic board. It requires to remove few components. The technician has never done it on a MAC.

Where: it is carried out in a properly equipped office (tools and light).



Selecting AR Validation - Categories

AR or not AR?

- AR not recommended
- AR application for this specific application might not provide any performance improvement or is technically limited
- AR strongly recommended

Hardware?

- HMD
- Micro Projector
- Small tablet
- Large tablet
- Display
- Spatial Display
- Projector

Development Platform?

- Low level programming language
- High level programming language
- High level programming language + ad hoc "programming libraries"
- Hardware SDK
- Commercial AR developing platform

Interaction method?

- All Audio and Video contents, both static and dynamic. Remote communication
- All Audio and Video contents, both static and dynamic
- CAD(static), images, text and audio
- Images, Text and Audio
- Text and Audio
- Only text

9 Select One or Two boxes for each category.

Selecting AR Validation– Case Studies

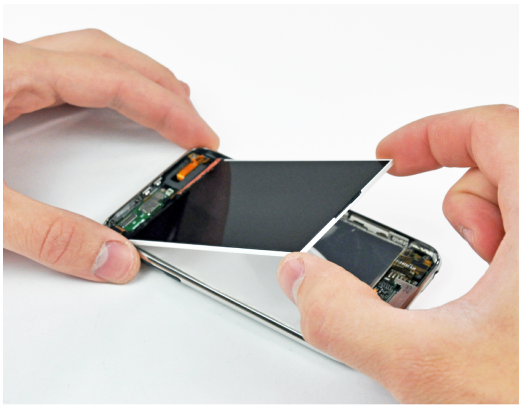
Case Study **4**

Non-Expert wants to fix hardware issue on a common IT device

Who: Self-though mechanical engineer. Used to manual operations.

What: Fix hardware issue. It requires both diagnosis and repair. Never done before but the sequence for the whole operation is "procedural"

Where: it is carried out in a not properly illuminated environment. Tools are available.



Selecting AR Validation - Categories

AR or not AR?

- AR not recommended
- AR application for this specific application might not provide any performance improvement or is technically limited
- AR strongly recommended

Hardware?

- HMD
- Micro Projector
- Small tablet
- Large tablet
- Display
- Spatial Display
- Projector

Development Platform?

- Low level programming language
- High level programming language
- High level programming language + ad hoc “programming libraries”
- Hardware SDK
- Commercial AR developing platform

Interaction method?

- All Audio and Video contents, both static and dynamic. Remote communication
- All Audio and Video contents, both static and dynamic
- CAD(static), images, text and audio
- Images, Text and Audio
- Text and Audio
- Only text

12 Select One or Two boxes for each category.

Selecting AR Validation– Case Studies

Case Study **5**

A Manufacturer wants to select AR for maintaining the machineries utilised for production. The aim is to allow any maintainer to do any maintenance operation regardless his area of expertise. (flexibility)

Who: Maintainers not specifically trained but with several years of industrial maintenance experience.

What: Maintain manufacturing equipment. Not “mass-diffused” machineries (such as laptops and cars). Wide range of complexity.

Where: it is carried out in a not properly equipped environment. Dusty and greasy machineries. Local and Remote locations compared to the headquarters (of the maintenance team)

Selecting AR Validation - Categories

AR or not AR?

- AR not recommended
- AR application for this specific application might not provide any performance improvement or is technically limited
- AR strongly recommended

Hardware?

- HMD
- Micro Projector
- Small tablet
- Large tablet
- Display
- Spatial Display
- Projector

Development Platform?

- Low level programming language
- High level programming language
- High level programming language + ad hoc "programming libraries"
- Hardware SDK
- Commercial AR developing platform

Interaction method?

- All Audio and Video contents, both static and dynamic. Remote communication
- All Audio and Video contents, both static and dynamic
- CAD(static), images, text and audio
- Images, Text and Audio
- Text and Audio
- Only text

15 Select One or Two boxes for each category.

Appendix B

This appendix contains additional material utilised for FARP's validation. More specifically,

1) Section B.1 contains the hard-copy user manual utilised for training the participants to become experts in dis/assembling the mock-up designed for validation purposes.
2) Section B.2 contains evidence of the FARP's software development. This includes Unity3D screenshots,
3) Section B.3 reports the main c# scripts and functions as well as the php queries utilised for communicating with the database.
4) Section B.4 contains the full dataset of time and errors gathered during the FARP's validation tests. The dataset has been analysed through SPSS.

B.1 Hard-copy manual utilised for FARP validation

These instructions describe the assembly and disassembly procedures designed for Fast Augmented Reality Programming (FARP) system test.

The assembly components are three:

1) The Top Component
2) The Base Component
3) The Board Component

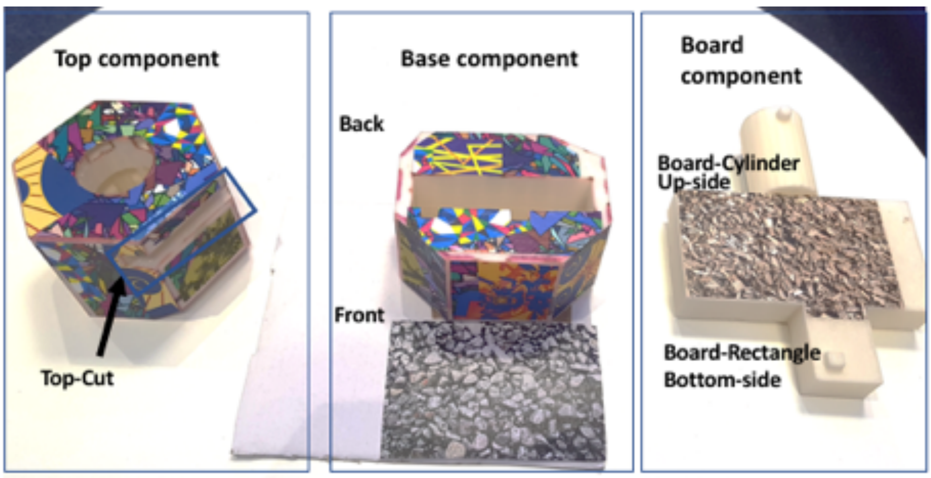


Figure B.1 FARP assembly components

The final configuration of the assembly is shown in Figure B.2.

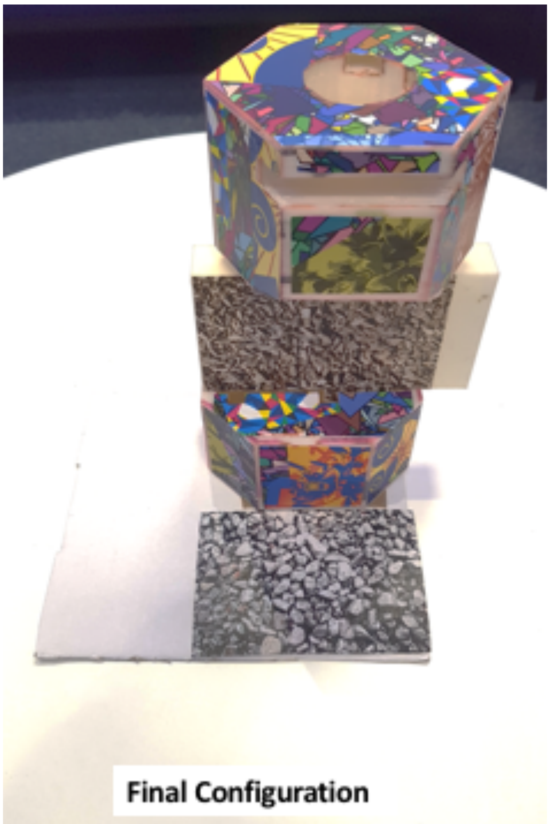


Figure B.2 Final configuration of FARP's assembly

Following, the dis/assembly procedures are described step-by step.

Assembly:

1. Never move the basement from the designated location
2. Holding the basement from the backside and the Board from the cylinder, place the Board-rectangle (bottom side) in the Basement. Use the path on the right. (up to the end)
3. Holding the Basement from the left and the Board from the Cylinder,
    a. Slide the Board upwards (1 cm)
    b. Slide the Board to the left (as much as possible)
4. Holding the Basement from the left and the Board from the Cylinder,
    a. Slide the Board to the right (0.5 cm)
    b. Slide the Board upwards (as much as possible)

   c. Slide the Board to the left (0,5 cm)
   d. Slide the Board downwards up to the end
5. Holding the Basement from the left and the Board from the Cylinder,
   a. Slide the board upwards (1 cm)
   b. Slide the board to the left (as much as possible)
   c. Slide the board downwards (as much as possible)
   d. Slide the board down-right (as much as possible)

See Notes – Last page.

6. Place the Top component on the designated area.
7. Rotate it with the Top-Cut facing the right.
8. Holding the Board from your left, Grab the Top and place it on the top Cylinder of the Board always with the Top-Cut facing the right.
   a. Note: this step has to be done quickly and without changing the orientation of the Top component.
9. Holding the Board from your left, Rotate the Top anticlockwise and, at the same time, try to slide it downwards.
10. Holding the Board from your left, Rotate the Top clockwise and, at the same time, try to slide it upwards. Than rotate anticlockwise.
11. Holding the Board from your left, Rotate the Top clockwise trying to slide it downwards.
12. Holding the Board from your left, rotate anticlockwise trying to slide upwards
13. Holding the Board from your left, Rotate clockwise as much as possible.

Final configuration picture. Top-Cut facing same direction as Board. Figure B.2.

Disassembly:

1. Never move the Basement from the designated area.
2. Holding the Board from your left, Rotate the Top anticlockwise (pulling upwards at the same time).
3. Holding the Board from your left, Rotate the Top clockwise (pulling upwards at the same time).

4. Holding the Board from your left, Rotate the Top anticlockwise (gently pushing down).
5. When found the path, move the Top component downwards trying to rate anticlockwise
6. Rotate anticlockwise pulling upwards
7. Rotate clockwise
8. Pull the Top-component upwards and position it on the designated area (on the left).
9. Holding the Basement from the left (back), Pull the Board on the left (up)
10. Pull the Board upwards pushing right
11. Slide the Board right pushing downwards (up to the end)
12. Pull the Board Upwards pushing right and then down, up to the end.
13. Repeat again step 12.
14. Pull upwards to remove the Board component and leave it on the designated area.

Notes

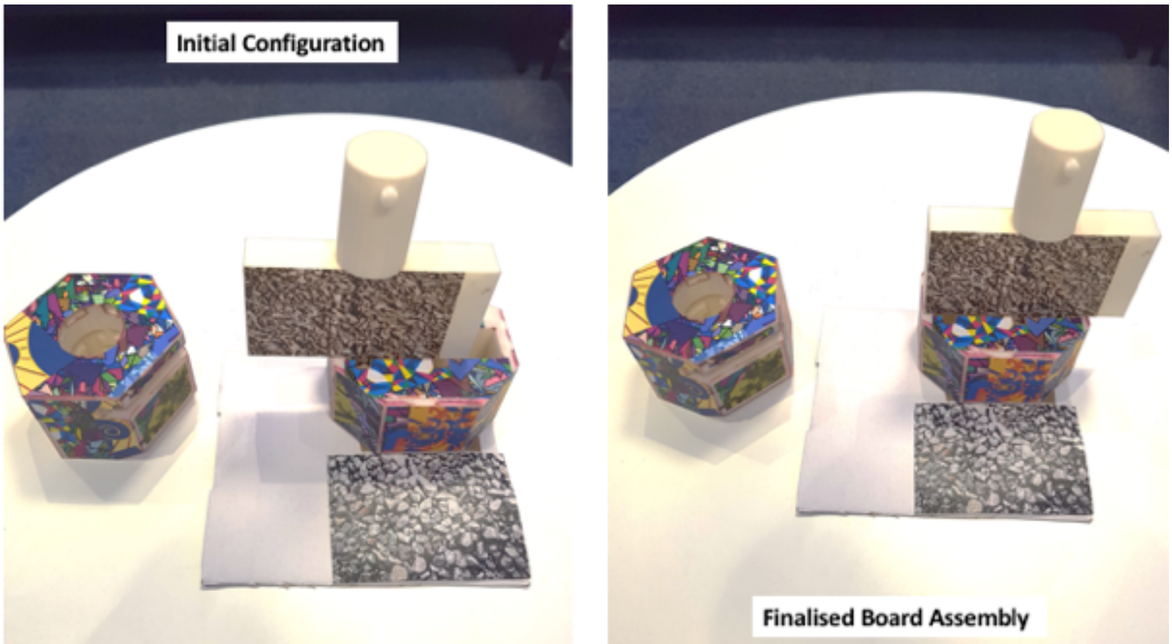


Figure B.3 Note showing initial configuration vs final board assembly

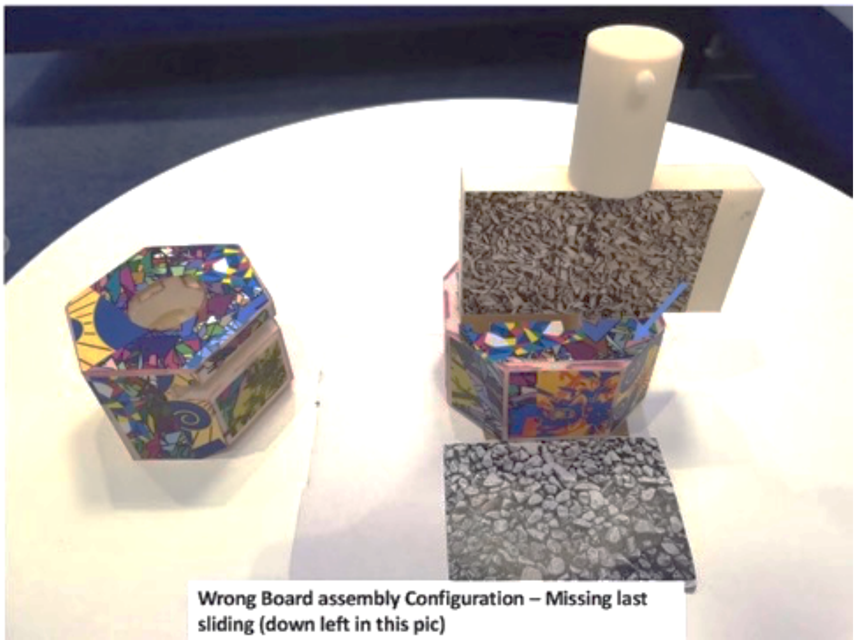


Figure B.4 Note showing wrong board assembly on the basement component.

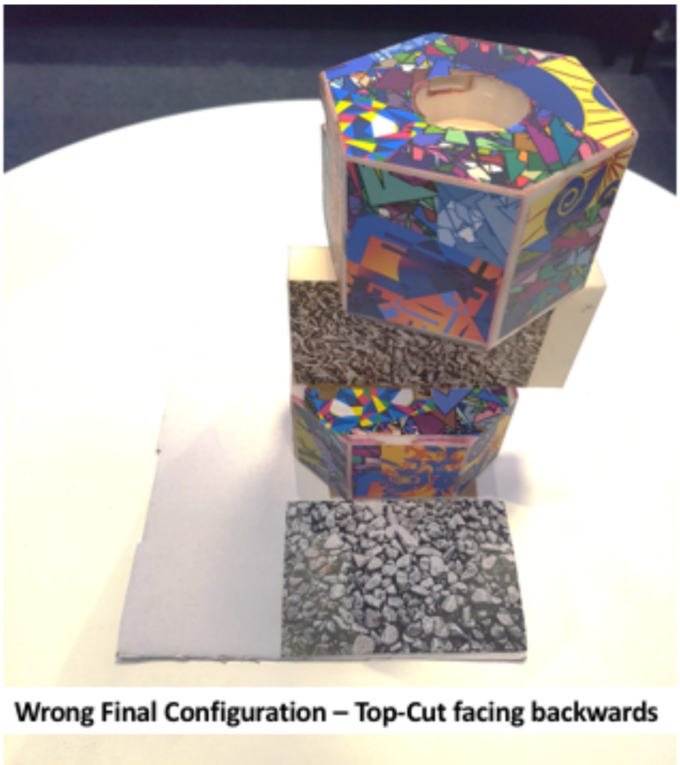


Figure B.5 Note showing wrong top component assembly on the board.

B.2 FARP software development evidence

This appendix is meant to show the reader the screenshots of the development platforms utilised for developing and building FARP application. More specifically, images from Unisty3D (the game engine), phpMyAdmin (the database) the query utilised for communicating with the database are reported.

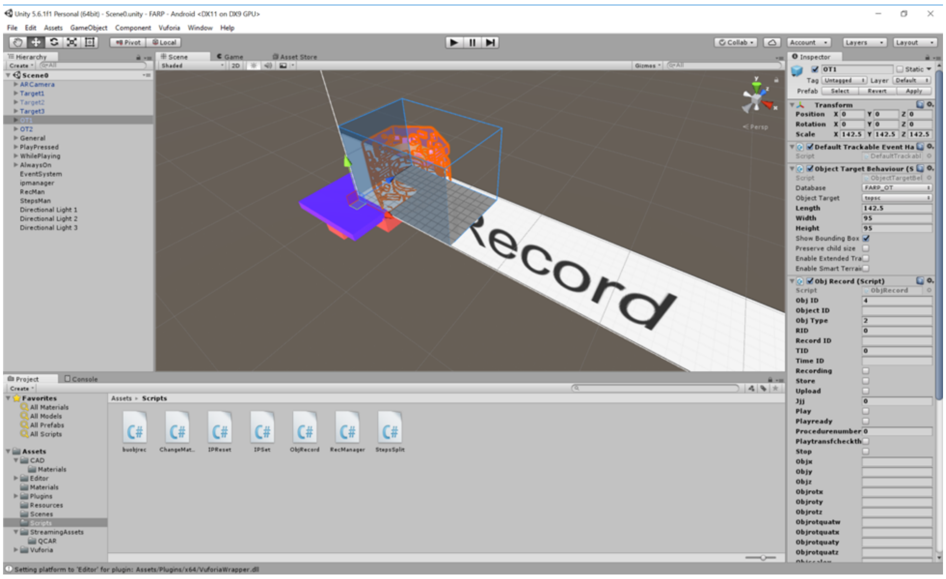


Figure B.6 Unity Scene screenshot. Image and Object targets in the hierarchy on the left. C# scripts folder on the bottom.

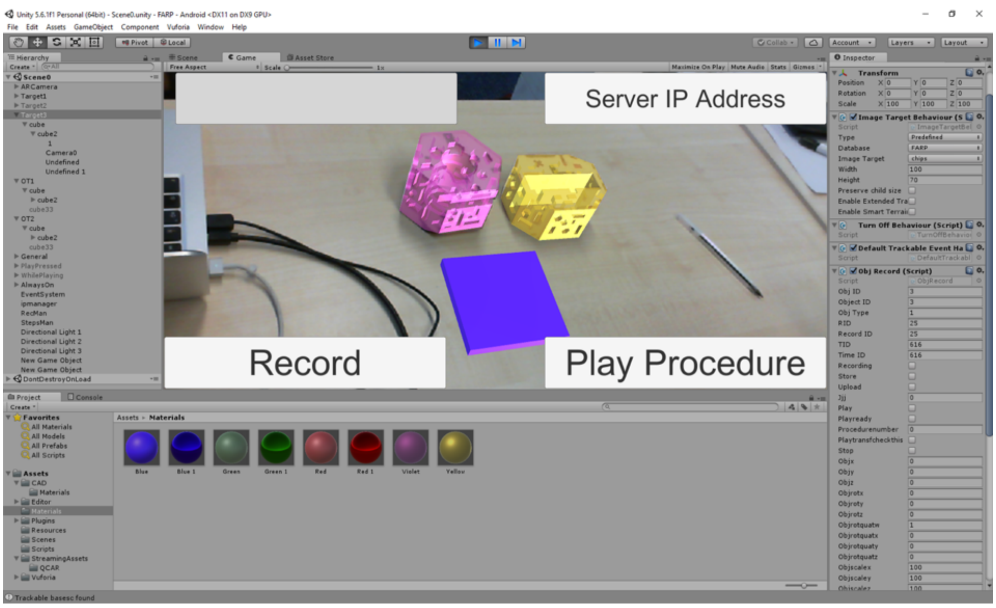


Figure B.7 Unity Game screenshot. Basement and Top components of mock-up assembly recognised and overlaid with virtual objects (in purple and yellow)

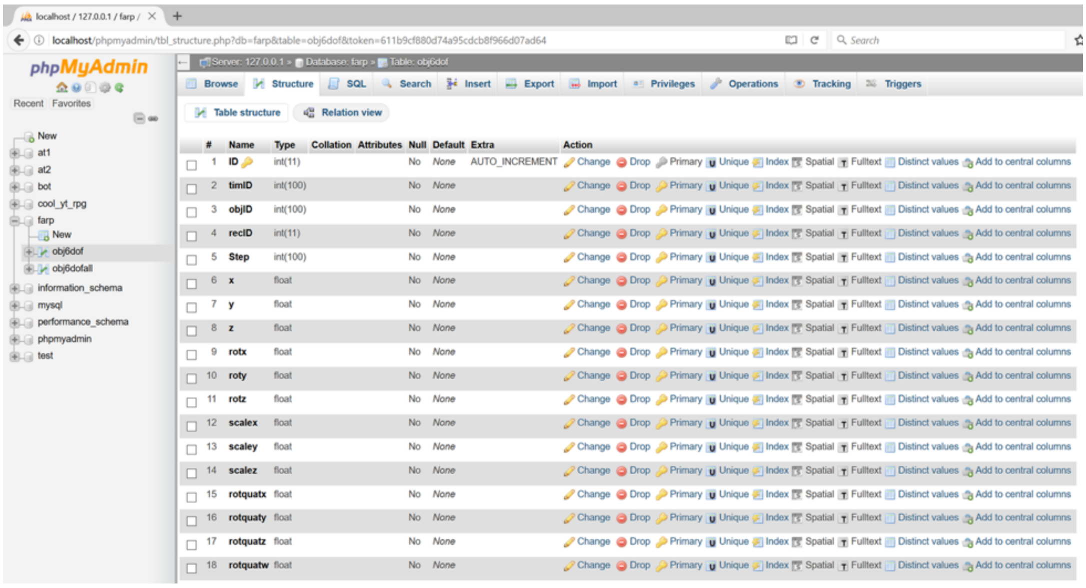


Figure B.8 FARP's database structure.

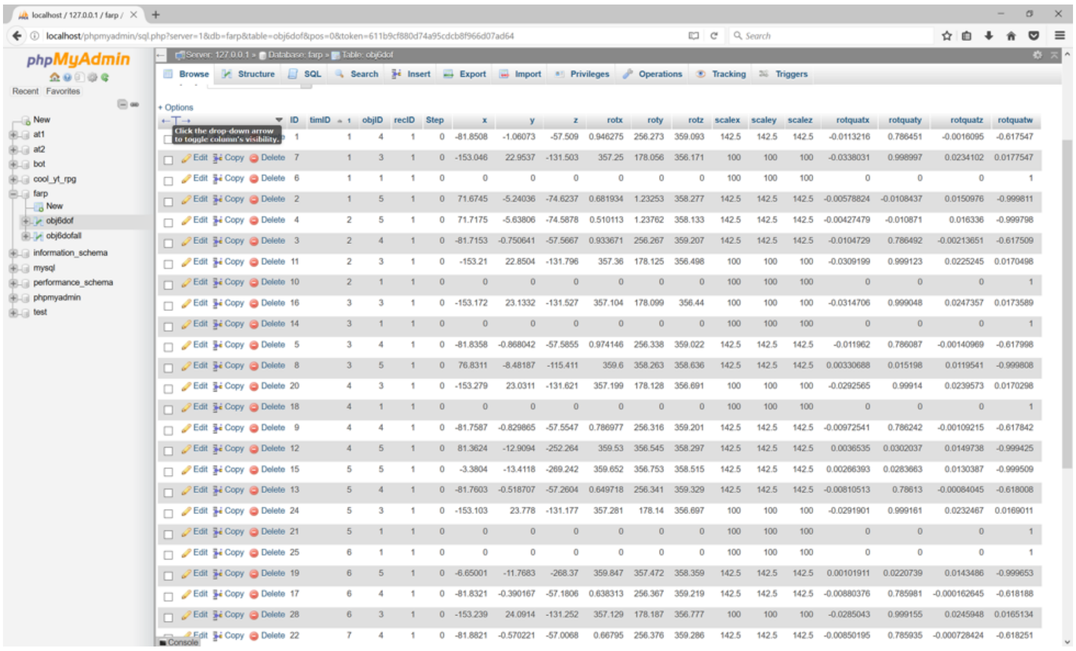


Figure B.9 FARP database filled throughout performing FARP's validation tests.

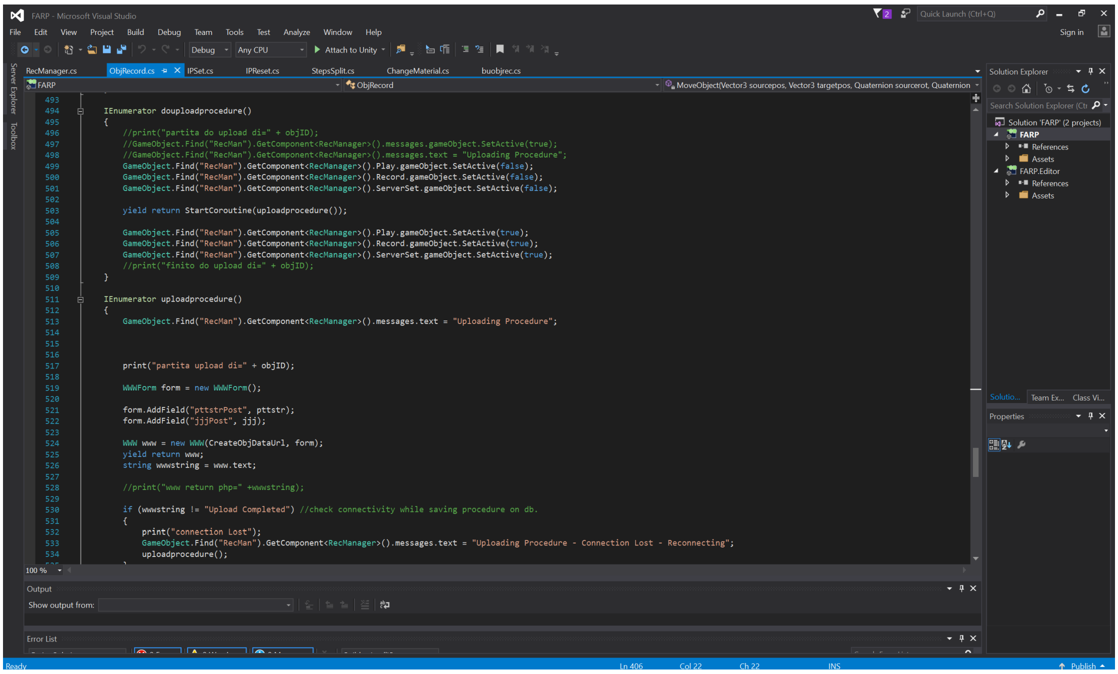


Figure B.10 ObjRecord.cs script in C# for locally saving the positions and orientations of each object separately

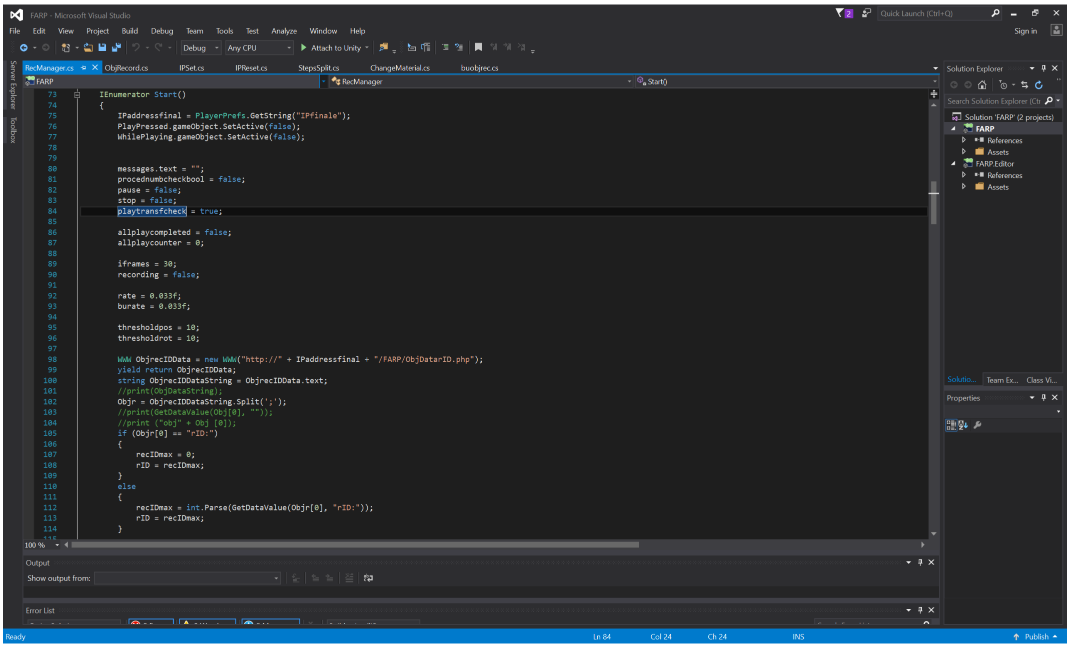


Figure B.11 RecManager.cs script in C# for managing the information collected by each object and send them to the database.

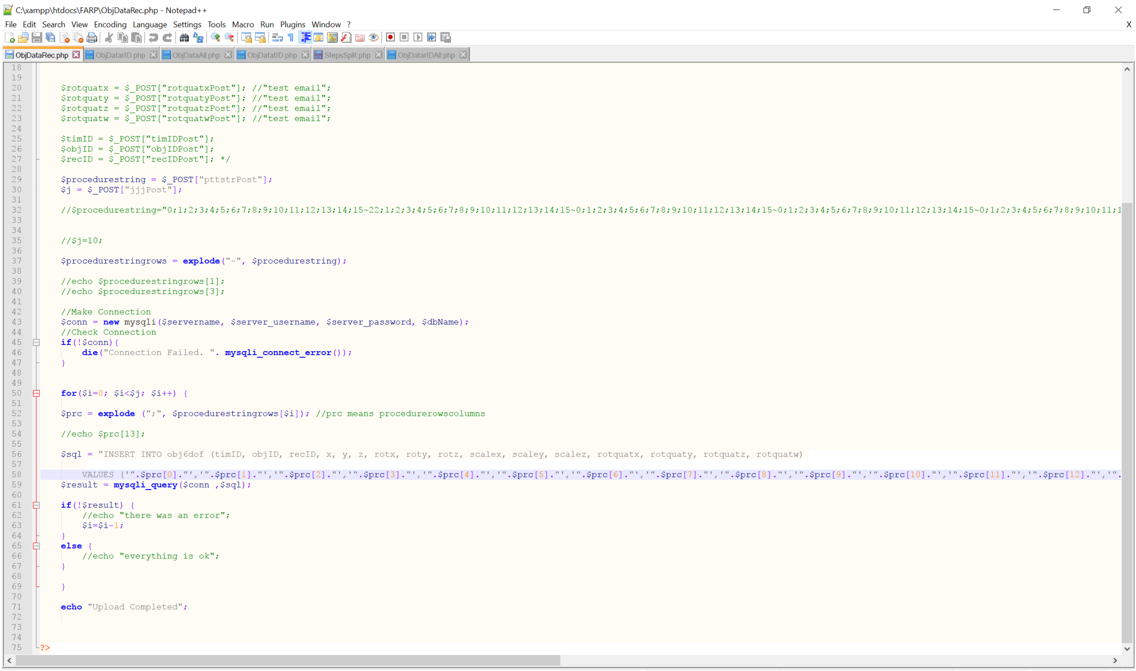


Figure B.12 ObjDataRec.php script in php saved on server for putting in communication Unity3D and MySQL.

B.3 FARP scripts

In this appendix are reported the main scripts, functions and query developed within FARP study.

This section is not meant for explaining every step of the programming process but only to allow reproducibility to experienced programmers. Mid-lever programming skills in Unity3D, c# and php are required for fully understanding the codes in this section.

Each script, function and query is commented in order to provide a better understanding to the reader.

The scripts and functions that have not been developed by the student have not been attached.

B.3.1 Record Manager Script (C#)


```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

//This script manages the status (record, play, stop, pause) of the virtual objects and communicates with the ObjRecord scripts attached
//to each component.
//This script manages the status messages at UI

//This script is not attached to the components.
//this script is attached to an empty object placed in the scene.

public class RecManager : MonoBehaviour {

    static public string IPaddressfinal; //IP address aquired from prefab
    public string[] Objr; //used for storing Object rID - recID
    public string[] Objt; //used for storing Object tID - timeID

    public int rID; //recordID for storing the current recording procedure
    public int recIDmax; //used for storing maximum recID found in db. Allows sequential writing of rIDs

    public int tID; //timeID for storing the current time of recording procedure
    public int timIDmax; //used for storing max time of current rec. Allows sequential writing of tIDs

    //counters
    public int k;
    public int i;
    public int iframes; //manages the speed of recording (eg. i % iframes == 0 records once every
                        //iframes frames => if iframes = 60 => once per second)
    public int j;


    //tracking status of objects
    public bool recording; //if true, the object is currently recording
    public bool store; //if true, the object is currently locally storing
    public bool upload; //if true, the object is currently uploaded
    public bool play; //if true, the object is currently playing - connected with playtranfcheckthis variable
    public bool stop; //if true, the object animation is stopped -> will restart from the beginning
    public bool pause; //if true, the object animation is paused -> will restart from where it was paused

    public int procedurenumber; //saves the procedure number indicated

    public float rate; //variable for UI messages delay
    public float burate; //variable for UI messages delay
```

```
    
    //thresholds are used for allowing the system to recognise as correct position/orientation the real components
    //positions and orientations when they differ from the expected ones only of few millimeters. The thesholds can be
    //changed based on the case study
    public int thresholdpos; //variable for providing allowance between the real position and the target position.
    public int thresholdrot; //variable for providing allowance between the real orientation and the target orientation.

    //counterplays are used for checking how many components are moving
    public int counterplayjman;
    public int allplaycounter;
    public bool allplaycompleted;

    public bool playtransfcheck;
    private bool procednumbcheckbool;


    //buttons and texts
    public Text rectext; //text variable on button Record. The text can change.
    public Button Record; // button Record

    public InputField ProcNumbPlay; //inputfield for inserting the proc. number as wished to be saved
    public Button Ok;
    public static string procnumbplaystring;
    public Text messages;
    public Button Play;

    public Button Pause;
    public Text pausetxt;


    //the canvas is used for grouping the UI.
    public Button ServerSet;
    public Canvas PlayPressed; //only buttons needed when play is pressed are shown
    public Canvas WhilePlaying; //only buttons needed when playing are shown
    public Canvas General; //only buttons needed when starting are shown

    //the following are the game objects in the hierarchy which represent the real components of the assembly.
    //In this case we have 1 anchor point + three components.
    public GameObject T1; //game object representing component 1 - in this case the anchor point.
    //public GameObject T2;
    public GameObject T3; //game object representing component 2 - the basement
    public GameObject T4; //game object representing component 3 - the board
    public GameObject T5; //game object representing component 4 - the top
```

```


    private string[] ObjrIDall; //used to check the last rID from db

    IEnumerator Start()
    {
        IPaddressfinal = PlayerPrefs.GetString("IPfinale");
        PlayPressed.gameObject.SetActive(false);
        WhilePlaying.gameObject.SetActive(false);


        messages.text = "";
        procednumbcheckbool = false;
        pause = false;
        stop = false;
        playtransfcheck = true;

        allplaycompleted = false;
        allplaycounter = 0;

        iframes = 30;
        recording = false;

        rate = 0.033f;
        burate = 0.033f;

        counterplayjman = 0;

        thresholdpos = 10;
        thresholdrot = 10;

        //extracting the maximum recID from db in order to assign the sequential rID to next recorded procedure
        WWW ObjrecIDData = new WWW("http://" + IPaddressfinal + "/FARP/ObjDatarID.php");
        yield return ObjrecIDData;
        string ObjrecIDDataString = ObjrecIDData.text;
        //print(ObjDataString);
        Objr = ObjrecIDDataString.Split(';');
        //print(GetDataValue(Obj[0], ""));
        //print ("obj" + Obj [0]);
        if (Objr[0] == "rID:")
        {
            recIDmax = 0;
            rID = recIDmax;
        }
        else
        {
            recIDmax = int.Parse(GetDataValue(Objr[0], "rID:"));
            rID = recIDmax;
        }

        //extracting the maximum timeID from db in order to assign the
```

```
          sequential tID to next recorded procedure
        WWW ObjtimIDData = new WWW("http://" + IPaddressfinal + "/FARP/ObjDatatID.php");
        yield return ObjtimIDData;
        string ObjtimIDDataString = ObjtimIDData.text;
        //print(ObjDataString);
        Objt = ObjtimIDDataString.Split(';');
        //print(GetDataValue(Obj[0], ""));
        //print ("obj" + Obj [0]);
        if (Objt[0] == "tID:")
        {
            timIDmax = 0;
            tID = timIDmax;
        }
        else
        {
            timIDmax = int.Parse(GetDataValue(Objt[0], "tID:"));
            tID = timIDmax;
        }

    }

    //subprogramme for removing '|' from string
    string GetDataValue(string data, string index)
    {
        string value = data.Substring(data.IndexOf(index) + index.Length);
        if (value.Contains("|")) value = value.Remove(value.IndexOf('|'));
        return value;
    }



    // Update is called once per frame
    void Update () {
        upload = false;
        play = false;

        if (k == 1)
        {
            recording = true;
            i = i + 1;
            //print("i value=" + i);
            if (i > 0)
            {
                //i manages the speed of recording (eg. i % 60 == 0 records once every 60 frames => once per second)
                if (i % iframes == 0)
                {
                    j = i / iframes;
                    tID = tID + 1;
                    store = true;
                }

```

```
                else
                {
                    store = false;
                }
            }
        }
       else
        {
          i = 0;
            recording = false;
        }

        if(allplaycounter == 3)
        {
            allplaycompleted = true;
        }
        else
        {
            allplaycompleted = false;
        }

        if(T1.GetComponent<ObjRecord>().playtransfcheckthis == true &&
          T3.GetComponent<ObjRecord>().playtransfcheckthis == true &&
          T4.GetComponent<ObjRecord>().playtransfcheckthis == true )
        {
            playtransfcheck = true;
        }

        if (T1.GetComponent<ObjRecord>().counterjplay !=
          T3.GetComponent<ObjRecord>().counterjplay ||
          T1.GetComponent<ObjRecord>().counterjplay !=
          T4.GetComponent<ObjRecord>().counterjplay ||
          T3.GetComponent<ObjRecord>().counterjplay !=
          T3.GetComponent<ObjRecord>().counterjplay)
        {
            counterplayjman = Mathf.Min(T1.GetComponent<ObjRecord>
              ().counterjplay, T3.GetComponent<ObjRecord>().counterjplay,
              T4.GetComponent<ObjRecord>().counterjplay);
        }
        else {
            counterplayjman = T1.GetComponent<ObjRecord>().counterjplay;
                }
    }

    //function for starting and stopping the recording. The value of k is
      changed to 1 when the record button is pressed.
    // to 0 if the previous value was 1. This function reads the value of k
      and acts on the UI. The actual recording based
    //k is made on the game objects (T2, T3 and T4)--> see ObjRecord script.
    public void kfunct()
    {
        if (k == 0)
        {
```

```
            k = k + 1;
            rID = rID + 1;
            rectext = Record.GetComponentInChildren<Text>();
            rectext.text = "Stop Record";
            Play.gameObject.SetActive(false);
            ServerSet.gameObject.SetActive(false);

            messages.text = "Recording...";

        }
        else
        {
            k = k - 1;
            rectext.text = "Record";
            Play.gameObject.SetActive(true);
            ServerSet.gameObject.SetActive(true);
            upload = true;
        }
    }


    //this function is activated when pressing the play button and selecting the procedure to be playied.
    //It manages the UI messages and runs the check of the current status. The actual animation is performed by the ObJRecod script
    //attached to each component.

    public void pfunct()
    {
        StartCoroutine(ppfunct());
    }

    //this coroutine is activated by pfunct()
    IEnumerator ppfunct()
    {
        if (ProcNumbPlay.text != "")
        {
            messages.text = "Looking for Procedure " + ProcNumbPlay.text + "...";

            //coroutine procedurechec() looks for the procedure number indicated and returns the messages
            //""Playing Procedure " + ProcNumbPlay.text""; if found
            //""Procedure: " + ProcNumbPlay.text + " is not Available""; if not found
            //the coroutine also changes the bool play from false to true if the procedure is found. ObjRecord will
            //than play the animaition

            yield return StartCoroutine (procedurecheck());

            if (procednumbcheckbool)
            {
```

```
                procedurenumber = int.Parse(ProcNumbPlay.text);
                messages.text = "Playing Procedure " + ProcNumbPlay.text;
                //Play.gameObject.SetActive(false);
                //Record.gameObject.SetActive(false);

                if (play == false)
                {
                    play = true;
                    procednumbcheckbool = false;
                }
            }

            else
            {
                messages.color = Color.red;
                messages.text = "Procedure: " + ProcNumbPlay.text + " is not 
                  Available";
                //Play.gameObject.SetActive(false);
                //Record.gameObject.SetActive(false);

                yield return new WaitForSecondsRealtime(5);

                Play.gameObject.SetActive(true);
                Record.gameObject.SetActive(true);
                messages.color = Color.black;
                messages.text = "";
            }
        }

        yield return null;
    }


    public void playmessage()
    {
        messages.text = "Input a Procedure Number";
    }

    public void emptymessage () {
        messages.text = "";
    }

    public void pausebtn()
    {
        if (pause == false)
        {
            pausetxt = Pause.GetComponentInChildren<Text>();
            pausetxt.text = "Continue";
            pause = true;
            StartCoroutine(messagepause());
            rate = 0;

        }
```

```
        else
        {
            pausetxt = Pause.GetComponentInChildren<Text>();
            pausetxt.text = "Pause";
            pause = false;
            StartCoroutine(messagepause());
            rate = 0.033f;
        }
    }

    IEnumerator messagepause()
    {
        if (pause == true)
        {
            messages.text = "Procedure in Pause";
        }
        else
        {
            messages.text = "Playing Procedure " + ProcNumbPlay.text;
        }
        yield return null;

    }

    public void stopbtn()
    {
        if (stop == false)
        {
            stop = true;
            StartCoroutine(messagestop());
        }

    }

    IEnumerator messagestop()
    {
        messages.text = "Wait! Procedure Stopped";
        yield return new WaitForSecondsRealtime(2);
        stop = false;
        messages.text = "";
    }


    IEnumerator procedurecheck()
    {


        WWW ObjrIDallData = new WWW("http://" + IPaddressfinal + "/FARP/ObjDatarIDall.php");
        string ObjrIDallDataString = ObjrIDallData.text;
        ObjrIDall = ObjrIDallDataString.Split(';');

```

```
        for (int j = 0; j < (ObjrIDall.Length); j++)
        {
            if (procednumbcheckbool == false)
            {
                if (ObjrIDall[j] == "recID:" + ProcNumbPlay.text)
                {
                    procednumbcheckbool = true;
                }
            }

            else {
                j = ObjrIDall.Length;
            }

            yield return null;
        }


    }
}
```

B.3.2 Object Record Script (C#)


```csharp
using UnityEngine;
using System.Collections;
using Vuforia;
using UnityEngine.UI;

//This scripts is attached to each component of the assembly
//This script acts based on RecManager instructions (Rec, play, stop, pause) only for the specific coponent to which it is attached.

//This script utilises Vuforia Library for recognising the objects in the FOV of the RGB camera.

public class ObjRecord : MonoBehaviour
{
    //private ObjectTargetBehaviour mObjectTargetBehaviour = null;
    private ImageTargetBehaviour mImageTargetBehaviour = null;
    private ObjectTargetBehaviour mObjectTargetBehaviour = null;

    //set of varialbles specifically linked to the component of the assembly.

    public int objID;
    public string objectID;
    public int objType;//1 for images and 2 for objects targets behaviours

    public int rID; //int recordID to tecord the task number or record number
    public string recordID;

    public int tID;
    public string timeID;

    // variables utilised for reading the actions from RecManager

    public bool recording;
    public bool store;
    public bool upload;
    public int jjj;

    public bool play;
    public bool playready;
    public int procedurenumber;

    public bool playtransfcheckthis;

    public int counterjplay;

    public bool stop;

    //Variables for storing comonents positions and orientations

    public string objx; //x position
    public string objy; //y position
    public string objz; //z position
```

```
    public string objrotx; // x axis rotation
    public string objroty; // y axis rotation
    public string objrotz; // z axis rotation

    //quaternions, also utilised for storing rotations. More reliable with respect above. - in this
    // case, x, y and z do not really represent the axis.
    public string objrotquatw;
    public string objrotquatx;
    public string objrotquaty;
    public string objrotquatz;

    // objects scale
    public string objscalex;
    public string objscaley;
    public string objscalez;

    //strings for temporarly storing transforms (positions and orientations vectors)
    private string[] dtt = new string[16];  //single transform in time
    private string pttstr;

    private float[,,] pttp = new float[16, 3600, 5]; //array of transforms. downloaded for play
    public string[] Objall;
    public string[] Objallsplit;

    public string teststring;
    public string indexx;

    static public string IPaddressfinal;
    string CreateObjDataUrl;

    //private variables, not accessible by other game objects or scripts.

    private Vector3 butransfpos;
    private Quaternion butransfrot;

    private Vector3 butransflocpos;
    private Quaternion butransflocrot;

    private Vector3 bucubetransfpos;
    private Quaternion bucubetransfrot;

    private Vector3 bucubetransflocpos;
    private Quaternion bucubetransflocrot;

    //st, end and stq enq, are the initial and final vectors, respectively for positions and rotations
    //which, once put in a for cycle, make the animation possible.

    private Vector3 st;
    private Vector3 end;
```

```
    private Quaternion stq;
    private Quaternion endq;
    public float speed = 100F;
    private float startTime;
    private float journeyLength;

    public Vector3 a;
    public Vector3 b;
    public Vector3 c;
    public float distance;

    public Vector3 t1;
    public Vector3 t2;
    public float tdiff;

    public float rate;
    public float burate;

    //inisialisation of the script. Gets IP and image target.
    void Start()
    {
        IPaddressfinal = PlayerPrefs.GetString("IPfinale");
        CreateObjDataUrl = "http://" + IPaddressfinal + "/FARP/
          ObjDataRec.php";

        playtransfcheckthis = false;

        // Note: This only works if this script is attached to an ImageTarget
        mImageTargetBehaviour = this.GetComponent<ImageTargetBehaviour>();
        mObjectTargetBehaviour = this.GetComponent<ObjectTargetBehaviour>();

        bucubetransflocpos = this.gameObject.transform.Find
          ("cube").localPosition;
        bucubetransflocrot = this.gameObject.transform.Find
          ("cube").localRotation;

        upload = false;
        play = false;
        playready = false;
        counterjplay = 0;
    }

    void Update()
    {
        if (objType == 1 && mImageTargetBehaviour == null)
        {
            return;
        }

        else if (objType == 2 && mObjectTargetBehaviour == null)
        {
            return;
        }
```

```csharp

        else
        {
            //gathers the current (because in updates) values of the variables from RecManager.
            rID = GameObject.Find("RecMan").GetComponent<RecManager>().rID;
            tID = GameObject.Find("RecMan").GetComponent<RecManager>().tID;

            recording = GameObject.Find("RecMan").GetComponent<RecManager>().recording;
            store = GameObject.Find("RecMan").GetComponent<RecManager>().store;
            upload = GameObject.Find("RecMan").GetComponent<RecManager>().upload;
            play = GameObject.Find("RecMan").GetComponent<RecManager>().play;
            stop = GameObject.Find("RecMan").GetComponent<RecManager>().stop;

            jjj = GameObject.Find("RecMan").GetComponent<RecManager>().j;
            procedurenumber = GameObject.Find("RecMan").GetComponent<RecManager>().procedurenumber;

            rate = GameObject.Find("RecMan").GetComponent<RecManager>().rate;

            Vector3 objpos = this.gameObject.transform.position;
            Vector3 objrot = this.gameObject.transform.rotation.eulerAngles;
            Vector3 objscale = this.gameObject.transform.lossyScale;
            Quaternion objrotquat = this.gameObject.transform.rotation;

            objx = objpos.x.ToString();
            objy = objpos.y.ToString();
            objz = objpos.z.ToString();

            objrotx = objrot.x.ToString();
            objroty = objrot.y.ToString();
            objrotz = objrot.z.ToString();

            objscalex = objscale.x.ToString();
            objscaley = objscale.x.ToString();
            objscalez = objscale.x.ToString();

            objrotquatx = objrotquat.x.ToString();
            objrotquaty = objrotquat.y.ToString();
            objrotquatz = objrotquat.z.ToString();
            objrotquatw = objrotquat.w.ToString();

            recordID = rID.ToString();
            objectID = objID.ToString();
            timeID = tID.ToString();

           if (recording)
            {
                if (store)
                {
```

```
                        buildprocedure(timeID, objectID, recordID, objx, objy, objz, objrotx, objroty, objrotz, objscalex, objscaley, objscalez, objrotquatx, objrotquaty, objrotquatz, objrotquatw, jjj);
                    }
                }

                if (upload)
                {
                    StartCoroutine(douploadprocedure());
                }

                if (play)
                {
                    playtransfcheckthis = false;

                    butransfpos = this.gameObject.transform.Find("cube").position;
                    butransfrot = this.gameObject.transform.Find("cube").rotation;

                    StartCoroutine(dodownloadprocedure(procedurenumber));
                    play = false;

                }

                if (playready)
                {
                    StartCoroutine(DoMoveObject());
                    print("play completed di objID=" + objID);
                    playready = false;
                }

                else
                {

                }
            }

            if (GameObject.Find("RecMan").GetComponent<RecManager>().allplaycompleted == true)
            {
                GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "";
                GameObject.Find("RecMan").GetComponent<RecManager>().General.gameObject.SetActive(true);
                GameObject.Find("RecMan").GetComponent<RecManager>().WhilePlaying.gameObject.SetActive(false);

                GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck = true;
                playtransfcheckthis = false;
                GameObject.Find("RecMan").GetComponent<RecManager>().allplaycounter = 0;
            }
```

```
    }

    IEnumerator DoMoveObject()
    {
        print("domoveobjstart di objID=" + objID);
        // print("ObjAll lengthD=" + Objall.Length);
        for (int j = 0; j < (Objall.Length - 1); j++)
        {
            print("j di obj[" + objID + "]=" + j);
            counterjplay = j;

            j= GameObject.Find("RecMan").GetComponent<RecManager>().counterplayjman;

            if (stop == false)
            {
                st = this.gameObject.transform.position;
                end = new Vector3(pttp[3, j, objID - 1], pttp[4, j, objID - 1], pttp[5, j, objID - 1]);

                stq = this.gameObject.transform.rotation;
                endq = new Quaternion(pttp[12, j, objID - 1], pttp[13, j, objID - 1], pttp[14, j, objID - 1], pttp[15, j, objID - 1]);

                if (j == 0)
                {

                    yield return StartCoroutine(MoveObject(st, end, stq, endq, journeyLength));
                }

                else if (j > 0)
                {
                    if (Vector3.Distance(this.transform.position, end) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdpos || Quaternion.Angle(this.transform.rotation, endq) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdrot)
                    {
                        GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck = false;
                        playtransfcheckthis = false;
                    }
                    else
                    {
                        this.gameObject.transform.Find("cube").localPosition = bucubetransflocpos;
                        this.gameObject.transform.Find("cube").localRotation = bucubetransflocrot;
                        playtransfcheckthis = true;
                    }

```

```
                    if (GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck == false)
                    {
                        j = j - 1;
                    }

                    yield return StartCoroutine(MoveObject(st, end, stq, endq, journeyLength));
                }
            }

            else
            {
                j = Objall.Length;
            }
        }

        this.gameObject.transform.Find("cube").localPosition = bucubetransflocpos;
        this.gameObject.transform.Find("cube").localRotation = bucubetransflocrot;
        GameObject.Find("RecMan").GetComponent<RecManager>().allplaycounter = GameObject.Find("RecMan").GetComponent<RecManager>().allplaycounter + 1;
    }

    IEnumerator MoveObject(Vector3 sourcepos, Vector3 targetpos, Quaternion sourcerot, Quaternion targetrot, float jLength)
    {
        float i = 0.0f;
        while (i < 1.0f)
        {
            if (stop == false)
            {
                if (GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck == false && playtransfcheckthis == true)
                {
                    i = i + rate;
                }
                else
                {
                    if (Vector3.Distance(this.transform.position, end) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdpos || Quaternion.Angle(this.transform.rotation, endq) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdrot)
                    {
                        i = i + rate;
                        this.gameObject.transform.Find("cube").position = Vector3.Lerp(sourcepos, targetpos, i);// -(((this.transform.position)/145)*100);
                        this.gameObject.transform.Find("cube").rotation = (Quaternion.Slerp(sourcerot, targetrot, i));
```

```
                    }
                    else
                    {
                        i = i + rate;
                    }
                }
             yield return new WaitForEndOfFrame();
            }

            else
            {
                i = 1.0f;
            }
        }
        yield return null;
        print("Moveobjcomplete di objID=" + objID);
    }

    IEnumerator dodownloadprocedure(int procnumb)
    {
        yield return StartCoroutine(downloadprocedure(procnumb));
        playready = true;
    }

    IEnumerator downloadprocedure(int procednumb)
    {
        WWWForm formdown = new WWWForm();
        formdown.AddField("procnumber", procednumb);
        formdown.AddField("objectID", objID);

        WWW ObjallData = new WWW("http://" + IPaddressfinal + "/FARP/ObjDataall.php", formdown); //note data all returns only recID1 - 1 should be a parameter
        yield return ObjallData;
        string ObjallDataString = ObjallData.text;
        Objall = ObjallDataString.Split(';');
        print("objall length=" + Objall.Length);

        for (int j = 0; j < (Objall.Length - 1); j++)
        {
            Objallsplit = Objall[j].Split('|');

            pttp[0, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[0], "timID:"));
            pttp[1, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[1], "objID:"));
            pttp[2, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[2], "recID:"));
            pttp[3, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[3], "x:"));
            pttp[4, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[4], "y:"));
            pttp[5, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[5],
```

```
                "z:"));
            pttp[6, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[6], "rotx:"));
            pttp[7, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[7], "roty:"));
            pttp[8, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[8], "rotz:"));
            pttp[9, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[9], "scalex:"));
            pttp[10, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[10], "scaley:"));
            pttp[11, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[11], "scalez:"));
            pttp[12, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[12], "rotquatx:"));
            pttp[13, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[13], "rotquaty:"));
            pttp[14, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[14], "rotquatz:"));
            pttp[15, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[15], "rotquatw:"));
        }
        yield return null;
    }

    string GetDataValue(string data, string index)
    {
        string value = data.Substring(data.IndexOf(index) + index.Length);
        if (value.Contains("|")) value = value.Remove(value.IndexOf('|'));
        return value;
    }

    IEnumerator douploadprocedure()
    {
       GameObject.Find("RecMan").GetComponent<RecManager>().Play.gameObject.SetActive(false);
        GameObject.Find("RecMan").GetComponent<RecManager>().Record.gameObject.SetActive(false);
        GameObject.Find("RecMan").GetComponent<RecManager>().ServerSet.gameObject.SetActive(false);

        yield return StartCoroutine(uploadprocedure());

        GameObject.Find("RecMan").GetComponent<RecManager>().Play.gameObject.SetActive(true);
        GameObject.Find("RecMan").GetComponent<RecManager>().Record.gameObject.SetActive(true);
        GameObject.Find("RecMan").GetComponent<RecManager>().ServerSet.gameObject.SetActive(true);
   }

    IEnumerator uploadprocedure()
    {
```

```
        GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure";
        WWWForm form = new WWWForm();
        form.AddField("pttstrPost", pttstr);
        form.AddField("jjjPost", jjj);
        WWW www = new WWW(CreateObjDataUrl, form);
        yield return www;
        string wwwstring = www.text;

        if (wwwstring != "Upload Completed") //check connectivity while saving procedure on db.
        {
            print("connection Lost");
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure - Connection Lost - Reconnecting";
            uploadprocedure();
        }

        else
        {
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure - Completed";
            yield return new WaitForSecondsRealtime(3);
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "";
            yield return null;
            print("finito upload di=" + objID);
        }
        pttstr = null;
    }

    public void buildprocedure(string timID, string objID, string recID, string x, string y, string z, string rotx, string roty, string rotz, string scalex, string scaley, string scalez, string rotquatx, string rotquaty, string rotquatz, string rotquatw, int jj)
    {
        dtt[0] = timID;
        dtt[1] = objID;
        dtt[2] = recID;
        dtt[3] = x;
        dtt[4] = y;
        dtt[5] = z;
        dtt[6] = rotx;
        dtt[7] = roty;
        dtt[8] = rotz;
        dtt[9] = scalex;
        dtt[10] = scaley;
        dtt[11] = scalez;
        dtt[12] = rotquatx;
        dtt[13] = rotquaty;
        dtt[14] = rotquatz;
        dtt[15] = rotquatw;

```

...Desktop\LAST FARP CC\FARPV3\Assets\Scripts\ObjRecord.cs 11

```
            int j = jj - 1;

            if (j < 3599)
            {
                if (j > 0)
                {
                    pttstr = pttstr + "~";
                }

                for (int i = 0; i < 16; i++)
                {
                   pttstr = pttstr + dtt[i] + ";";
                }
            }

            else
            {
                print("Preocedure is too long");
            }
        }
    }
```

B.3.3 IP set (C#)

...rdo\Desktop\LAST FARP CC\FARPV3\Assets\Scripts\IPSet.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.SceneManagement;
using UnityEngine.UI;

//This script is utilised in Scene0 for setting the IP address which allows the 
   comunication with the db.

public class IPSet : MonoBehaviour {

    public InputField IPinput; //the text block where the IP has to be written
    public static string IP; //the IP string

    private void Awake()
    {
       // DontDestroyOnLoad(this);
    }

    // Use this for initialization
    void Start()
    {
        if (IP != null)
           IPinput.text = IP;
    }

    // called by the InputFIeld
    public void inputip(string newIP)
    {
        IP = newIP;
        PlayerPrefs.SetString("IPfinale", IP); //locally saves the IP address.
        SceneManager.LoadScene("Scene0");
    }

}
```

B.3.4 Change Material(C#)

...op\LAST FARP CC\FARPV3\Assets\Scripts\ChangeMaterial.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

//this script allowes changing the material (and therefore the colour) of the components recognised
//once their status changes from "playtranfcheckthis == false" to "playtranfcheckthis == true".
//"playtranscheckthis variable is called from "ObjRecod" script attached to each component.

//When the AR step-by-step procedures suggests that a component has to move from his real location/orientation
//to another real location/orientation, the virtual object representing the real component will be RED and
//the will animate. When the real component reaches the target position, the virtual object becomes GREEN.

//this script has to be attached to the component.

public class ChangeMaterial : MonoBehaviour {


    public Material bumaterial; //RED material
    public Material GreenMaterial; //GREEN material

    // Use this for initialization
    void Start() {
        //GreenMaterial = Resources.Load("Green", typeof(Material)) as Material;
    }

    // Update is called once per frame
    void Update() {

        if (this.GetComponentInParent<ObjRecord>().playtransfcheckthis == true)
        {
            this.GetComponent<Renderer>().material = GreenMaterial;
        }

        else
        {
            this.GetComponent<Renderer>().material = bumaterial;
        }
    }
}
```

B.3.5 Autofocus (C#)

...Desktop\LAST FARP CC\FARPV3\Assets\Scripts\Autofocus.cs 1

```csharp
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using Vuforia;

//Camera autofocus script for allowing the continuous focus. Necessary for efficiently running Vuforia.

public class Autofocus : MonoBehaviour
{
    void Start()
    {
        VuforiaARController.Instance.RegisterVuforiaStartedCallback(OnVuforiaStarted);
        VuforiaARController.Instance.RegisterOnPauseCallback(OnPaused);
    }

    private void OnVuforiaStarted()
    {
        CameraDevice.Instance.SetFocusMode(
            CameraDevice.FocusMode.FOCUS_MODE_CONTINUOUSAUTO);
    }

    private void OnPaused(bool paused)
    {
        if (!paused) // resumed
        {
            // Set again autofocus mode when app is resumed
            CameraDevice.Instance.SetFocusMode(
                CameraDevice.FocusMode.FOCUS_MODE_CONTINUOUSAUTO);
        }
    }
}
```

B.3.6 Object Data All (php)

```php
<?php
   //query for calling all data related to procedur pn and object oID

     $pn = $_POST["procnumber"]; //"Lucas.Test AC";
     $oID = $_POST["objectID"]; //"Lucas.Test AC";

    //Make Connection
 $conn = mysqli_connect('89.46.111.46','Sql1112120','1r64275t1p','Sql1112120_5');
    //Check Connection
    if(!$conn){
        die("Connection Failed. ". mysqli_connect_error());
    }

    $sql = "SELECT timID, objID, recID, x, y, z, rotx, roty, rotz, scalex, scaley,
    scalez, rotquatx, rotquaty, rotquatz, rotquatw  FROM obj6dof WHERE recID = '$pn'
    AND objID = '$oID' ORDER BY timID"; //AND objID = '$oID'
    $result = mysqli_query($conn ,$sql);
    echo $pn;

    if(mysqli_num_rows($result) > 0){
        //show data for each row

        while($row = mysqli_fetch_assoc($result)){
            echo "timID:".$row['timID'] ."|objID:".$row['objID']
            ."|recID:".$row['recID'] ."|x:".$row['x'] ."|y:".$row['y']
            ."|z:".$row['z'] ."|rotx:".$row['rotx'] ."|roty:".$row['roty']
            ."|rotz:".$row['rotz'] ."|scalex:".$row['scalex']
            ."|scaley:".$row['scaley'] ."|scalez:".$row['scalez']
            ."|rotquatx:".$row['rotquatx'] ."|rotquaty:".$row['rotquaty']
            ."|rotquatz:".$row['rotquatz'] ."|rotquatw:".$row['rotquatw'] . ";";
        }
    }

?>
```

B.3.7 Object Data rID (php)

```php
<?php
//query for calling rID data related to procedur pn and object oID

    //Make Connection
    $conn = mysqli_connect('89.46.111.46','Sql1112120','1r64275t1p','Sql1112120_5')
    //Check Connection
    if(!$conn){
        die("Connection Failed. ". mysqli_connect_error());
    }

    //$sql = "SELECT max(recID) AS rID FROM obj6dof";
    $sql = "SELECT max(recID) AS rID FROM obj6dof";
    $result = mysqli_query($conn ,$sql);


    if(mysqli_num_rows($result) > 0){
        //show data for each row

       while($row = mysqli_fetch_assoc($result)){
            //echo "" .$row['rID'] . "";
           echo "rID:".$row['rID'] . ";";
        }
    }

?>
```

B.4 Test Anova Database

In this section is reported the table containing all the data (time and errors) collected through FARP's validation test. The table is structured as follows:

On the first column is reported the maintenance support method: Instructions Vs AR.

In columns 2 to 6 are reported the time in seconds collected for tasks 1 to 4 plus the complete dis/assembly procedure.

In columns 8 to 12 are reported the number of errors collected for tasks 1 to 4 plus the complete dis/assembly procedure.

Column 7 only replicates column 1 information: 1=Instructions, 2=AR.

Table B.1 FARP's validation dataset.

VAR00019	Task 1	Task 2	Task 3	Task 4	Task Tot	VAR00001	Errors1	Errors2	Errors3	Errors4	Errors Tot
Instructions	170.00	340.00	182.00	83.00	760.00	1.00	1.00	1.00	1.00	1.00	4.00
Instructions	139.00	278.00	207.00	95.00	760.00	1.00	1.00	1.00	2.00	1.00	5.00
Instructions	180.00	264.00	195.00	140.00	715.00	1.00	1.00	0.00	1.00	0.00	2.00
Instructions	267.00	267.00	138.00	103.00	748.00	1.00	1.00	0.00	0.00	1.00	2.00
Instructions	213.00	299.00	197.00	79.00	746.00	1.00	1.00	0.00	1.00	2.00	4.00
Instructions	112.00	299.00	186.00	121.00	786.00	1.00	2.00	1.00	1.00	1.00	5.00
Instructions	168.00	168.00	351.00	58.00	715.00	1.00	2.00	1.00	4.00	2.00	9.00
Instructions	267.00	283.00	200.00	100.00	760.00	1.00	2.00	1.00	1.00	1.00	5.00
Instructions	138.00	314.00	156.00	100.00	850.00	1.00	1.00	1.00	2.00	3.00	7.00
Instructions	129.00	374.00	214.00	98.00	691.00	1.00	0.00	2.00	1.00	0.00	3.00
Instructions	129.00	257.00	257.00	107.00	815.00	1.00	2.00	1.00	1.00	2.00	6.00
Instructions	224.00	259.00	162.00	67.00	750.00	1.00	1.00	1.00	1.00	4.00	7.00

VAR00019	*Task 1*	*Task 2*	*Task 3*	*Task 4*	*Task Tot*	*VAR00001*	*Errors1*	*Errors2*	*Errors3*	*Errors4*	*Errors Tot*
Instructions	184.00	369.00	263.00	61.00	700.00	1.00	1.00	1.00	1.00	2.00	5.00
Instructions	143.00	334.00	319.00	64.00	870.00	1.00	1.00	2.00	2.00	1.00	6.00
Instructions	202.00	346.00	316.00	58.00	860.00	1.00	0.00	1.00	1.00	1.00	3.00
AR	50.00	120.00	80.00	60.00	310.00	2.00	0.00	0.00	0.00	1.00	1.00
AR	120.00	260.00	220.00	70.00	670.00	2.00	0.00	0.00	0.00	0.00	0.00
AR	20.00	120.00	80.00	20.00	240.00	2.00	0.00	0.00	1.00	0.00	1.00
AR	30.00	120.00	160.00	30.00	340.00	2.00	1.00	0.00	0.00	1.00	2.00
AR	30.00	240.00	180.00	60.00	510.00	2.00	0.00	0.00	0.00	0.00	0.00
AR	70.00	220.00	120.00	50.00	460.00	2.00	0.00	0.00	0.00	0.00	0.00
AR	115.00	263.00	120.00	60.00	558.00	2.00	1.00	0.00	0.00	1.00	2.00
AR	80.00	300.00	120.00	70.00	570.00	2.00	1.00	1.00	1.00	0.00	3.00
AR	110.00	298.00	229.00	100.00	737.00	2.00	1.00	0.00	0.00	1.00	2.00
AR	130.00	210.00	135.00	80.00	555.00	2.00	0.00	0.00	1.00	0.00	1.00
AR	80.00	230.00	140.00	120.00	570.00	2.00	1.00	0.00	0.00	0.00	0.00
AR	90.00	195.00	180.00	80.00	545.00	2.00	0.00	0.00	1.00	1.00	2.00
AR	80.00	170.00	140.00	90.00	480.00	2.00	1.00	0.00	1.00	1.00	4.00
AR	120.00	235.00	120.00	60.00	535.00	2.00	1.00	1.00	0.00	1.00	3.00
AR	60.00	160.00	160.00	55.00	435.00	2.00	1.00	0.00	1.00	0.00	2.00

Appendix C

This appendix contains additional material utilised for ARRA's validation. More specifically,

1) Section C.1 contains the written guide utilised by the observer for carrying out ARRA's validation test. More specifically it includes the experiment set-up information and outlines what to do in case of deviation from the pre-determined test path.
2) Section C.2 reports the main c# scripts and functions as well as the php queries utilised for communicating with the database
3) Section C.3 contains the full dataset of time and errors gathered during the FARP's validation tests. The dataset has been analysed through SPSS.

C.1 ARRA Test Notes

This test has been designed to verify the AR system developed by the student: ARRA.

In order to succeed in the test and collecting robust data, it is really important that the participants take part at the test following a rigorous methodology.

The test aims to prove that ARRA:

1) overcomes spatial referencing issues
2) overcomes communication limitations (technical and linguistic)

Both compared to voice and video call.

<u>Environment Set-Up:</u> In order to enhance the object recognition and tracking, the environment has to be controlled.

<u>Location</u>: Opex Lab in BLD 30

<u>Lighting</u>: Select condition 1

<u>Table Set Up</u>: The table will be prepared with a uniform dark "tablecloth"

Camera and Screen: The Camera will be pointing in the same direction as the participant sight. The distance between the camera and the table will be of around 80 cm. The screen will be located in front of the participant. The objects/ assembly will be placed between the screen and the participant.

Experiment Timeline:

Firstly – Initial Questionnaire

If(experienced in maintenance) => Content Creator

If(experienced in AR) => Content Tester

Secondly – Test

If(Content Creator)

The task consists in Creating a Maintenance procedure utilising the Puzzle provided. Maintenance instructions will be provided. The Participant will:

Solve the Puzzle without Instructions (#)

Solve the Puzzle with Instructions

Solve the Puzzle with Instruction again(#)

Solve the Puzzle with Instruction again(#)

Create Assembly Content (&)

Create Disassembly Content (&)

If(Content Tester)

The task consists in utilising the Contents created by a Content Creator. The Participant will:

1) Solve the Puzzle with AR (assembly content 1st creator) (*)

2) Solve the Puzzle with AR (disassembly content 2nd creator) (*)

Thirdly – Questionnaire for Participant (depending on the role)

Note:

The participants will never be allowed to see the bottom side of the objects and inside the objects.

Notes for all Participants:

The participants should always avoid creating occlusions between the camera and the objects. The objects should be handled from the sides and moved parallel to the table surface avoiding lifting them up.

-If the tracking is lost, the participant will be asked to perform the task again.

(#) Errors and Time will be tracked

(&) Feedback will be collected

(*) Errors and Time will be tracked in both: following the AR procedure and performing the maintenance task itself.

C.2 ARRA scripts

In this appendix are reported the main scripts, functions and query developed within ARRA study.

This section is not meant for explaining every step of the programming process but only to allow reproducibility to experienced programmers. Mid-lever programming skills in Unity3D, c# and php are required for fully understanding the codes in this section.

Each script, function and query is commented in order to provide a better understanding to the reader.

The scripts and functions that have not been developed by the student have not been attached.

C.2.1 Object Record requester (C#)

... FARP RA (tbc)\FARPREMREQV0\Assets\Scripts\ObjRecord.cs 1

```
using UnityEngine;
using System.Collections;
using Vuforia;
using UnityEngine.UI;

//this script is attached to each component of the assembly.

//It writes on the real object database and reads from the virtual objects database.
//therefore it send the real object transfrom to the remote assistant
//the remote assistant writes the suggestions (animations) through the virtual manipulater on
//the virtual datatabase
//and this script reads the suggested transforms from the virtual database.
//always writing on the real db the real obj positions for allowing the assistant to check
//throughout the maintenance procedure

public class ObjRecord : MonoBehaviour
{
    private ImageTargetBehaviour mImageTargetBehaviour = null;
    public int objID;
    public string objectID;

    public bool Moving;

    public int rID; //int recordID to tecord the task number or record number
    public string recordID;

    public int tID;
    public string timeID;

    public bool recording;
    public bool store;
    public bool upload;
    public int jjj;

    public bool play;
    public bool playthis;
    public bool playready;
    public int procedurenumber;

    public bool playtransfcheckthis;

    public int counterjplay;

    public bool stop;

    public string objx;
    public string objy;
    public string objz;

    public string objrotx;
```

```
    public string objroty;
    public string objrotz;

    public string objrotquatw;
    public string objrotquatx;
    public string objrotquaty;
    public string objrotquatz;

    public string objscalex;
    public string objscaley;
    public string objscalez;

    private string[] dtt = new string[16];  //single transform in time
    //private string[,] ptt = new string[16, 3600]; //array of transforms. each row is one dtt.
    private string pttstr;

    private float[,,] pttp = new float[16, 3600, 5]; //array of transforms. downloaded for play
    public string[] Objall;
    public string[] Objallsplit;

    public string teststring;
    public string indexx;

    static public string IPaddressfinal;
    string CreateObjDataUrl;

    private Vector3 butransfpos;
    private Quaternion butransfrot;

    private Vector3 butransflocpos;
    private Quaternion butransflocrot;

    private Vector3 bucubetransfpos;
    private Quaternion bucubetransfrot;

    private Vector3 bucubetransflocpos;
    private Quaternion bucubetransflocrot;

    private Vector3 buposstoreyn;
    private Quaternion burotstoreyn;

    private Vector3 st;
    private Vector3 end;
    private Quaternion stq;
    private Quaternion endq;
    public float speed = 100F;
    private float startTime;
    private float journeyLength;

    public Vector3 a;
    public Vector3 b;
```

```
    public Vector3 c;
    public float distance;

    public Vector3 t1;
    public Vector3 t2;
    public float tdiff;

    public float rate;
    public float burate;

    void Start()
    {
        IPaddressfinal = PlayerPrefs.GetString("IPfinale");
        CreateObjDataUrl = "http://" + IPaddressfinal + "/FARP/realObjDataRecbunostring.php";

        playtransfcheckthis = false;
        Moving = false;
        mImageTargetBehaviour = this.GetComponent<ImageTargetBehaviour>();

        bucubetransflocpos = this.gameObject.transform.Find("cube").localPosition;
        bucubetransflocrot = this.gameObject.transform.Find("cube").localRotation;
        upload = false;
        play = false;
        playthis = false;
        playready = false;
        //procedurenumber = 2;
        counterjplay = 0;

    }

    void Update()
    {

        rID = GameObject.Find("RecMan").GetComponent<RecManager>().rID;
        tID = GameObject.Find("RecMan").GetComponent<RecManager>().tID;

        recording = GameObject.Find("RecMan").GetComponent<RecManager>().recording;
        store = GameObject.Find("RecMan").GetComponent<RecManager>().store;
        upload = GameObject.Find("RecMan").GetComponent<RecManager>().upload;
        play = GameObject.Find("RecMan").GetComponent<RecManager>().play;
        stop = GameObject.Find("RecMan").GetComponent<RecManager>().stop;

        jjj = GameObject.Find("RecMan").GetComponent<RecManager>().j;
        procedurenumber = GameObject.Find("RecMan").GetComponent<RecManager>().procedurenumber;

        rate = GameObject.Find("RecMan").GetComponent<RecManager>().rate;

        Vector3 objpos = this.gameObject.transform.position;
```

```
        Vector3 objrot = this.gameObject.transform.rotation.eulerAngles;
        Vector3 objscale = this.gameObject.transform.lossyScale;
        Quaternion objrotquat = this.gameObject.transform.rotation;

        objx = objpos.x.ToString();
        objy = objpos.y.ToString();
        objz = objpos.z.ToString();

        objrotx = objrot.x.ToString();
        objroty = objrot.y.ToString();
        objrotz = objrot.z.ToString();

        objscalex = objscale.x.ToString();
        objscaley = objscale.x.ToString();
        objscalez = objscale.x.ToString();

        objrotquatx = objrotquat.x.ToString();
        objrotquaty = objrotquat.y.ToString();
        objrotquatz = objrotquat.z.ToString();
        objrotquatw = objrotquat.w.ToString();

        recordID = rID.ToString();
        objectID = objID.ToString();
        timeID = tID.ToString();
      if (recording)
        {
            if (Vector3.Distance(this.gameObject.transform.position,
              buposstoreyn) < 0.5)
            {
                store = false;
                buposstoreyn = this.gameObject.transform.position;
            }
            if (store)
            {
                realCreateObjDof(timeID, objectID, recordID, objx, objy, objz,
                   objrotx, objroty, objrotz, objscalex, objscaley, objscalez,
                   objrotquatx, objrotquaty, objrotquatz, objrotquatw);
                buposstoreyn = this.gameObject.transform.position;
            }
        }

        if (upload)
        {
            StartCoroutine(douploadprocedure());
       }

        if (playthis)
        {
            print("oooooooocplay di obj[" + objID + "]");
            playtransfcheckthis = false;
            butransfpos = this.gameObject.transform.Find("cube").position;
            butransfrot = this.gameObject.transform.Find("cube").rotation;
            StartCoroutine(dodownloadprocedure(procedurenumber));
```

```
            playthis = false;
        }

        if (playready)
        {
            StartCoroutine(DoMoveObject());
            print("play completed ooooo di objID=" + objID);
            playready = false;
        }

        else
        {

        }

        if (GameObject.Find("RecMan").GetComponent<RecManager>().allplaycompleted == true)
        {
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "";
            GameObject.Find("RecMan").GetComponent<RecManager>().General.gameObject.SetActive(true);
            GameObject.Find("RecMan").GetComponent<RecManager>().WhilePlaying.gameObject.SetActive(false);
            GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck = true;
            playtransfcheckthis = false;
            GameObject.Find("RecMan").GetComponent<RecManager>().allplaycounter = 0;
        }
    }

    IEnumerator DoMoveObject()
    {
        print("domoveobjstart di objID=" + objID);
        // print("ObjAll lengthD=" + Objall.Length);
        for (int j = 0; j < (Objall.Length - 1); j++)
        {
            print("j di obj[" + objID + "]=" + j);
            counterjplay = j;
            j = GameObject.Find("RecMan").GetComponent<RecManager>().counterplayjman;

            if (stop == false)
            {
              st = this.gameObject.transform.position;
                end = new Vector3(pttp[3, j, objID - 1], pttp[4, j, objID - 1], pttp[5, j, objID - 1]);
                stq = this.gameObject.transform.rotation;
                endq = new Quaternion(pttp[12, j, objID - 1], pttp[13, j, objID - 1], pttp[14, j, objID - 1], pttp[15, j, objID - 1]);

                if (j == 0)
```

```
                    {
                        yield return StartCoroutine(MoveObject(st, end, stq, endq, journeyLength));
                    }

                    else if (j > 0)
                    {
                        if ((Vector3.Distance(this.transform.position, end) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdpos || Quaternion.Angle(this.transform.rotation, endq) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdrot) && (this.Moving == true))
                        {
                            GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck = false;
                            playtransfcheckthis = false;
                            print("here end of obj[] pos = [" + end.x + "][" + end.y + "][" + end.z + "]");
                        }

                    else
                    {
                        this.gameObject.transform.Find("cube").localPosition = bucubetransflocpos;
                        this.gameObject.transform.Find("cube").localRotation = bucubetransflocrot;
                        playtransfcheckthis = true;
                    }


                    if (GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck == false)
                    {

                        j = j - 1;
                    }
                    yield return StartCoroutine(MoveObject(st, end, stq, endq, journeyLength));
                    }
                }

                else
                {
                    j = Objall.Length;
                }
            }
            this.gameObject.transform.Find("cube").localPosition = bucubetransflocpos;
             this.gameObject.transform.Find("cube").localRotation = bucubetransflocrot;
             GameObject.Find("RecMan").GetComponent<RecManager>().allplaycounter = GameObject.Find("RecMan").GetComponent<RecManager>().allplaycounter
```

```
            + 1;
    }

    IEnumerator MoveObject(Vector3 sourcepos, Vector3 targetpos, Quaternion sourcerot, Quaternion targetrot, float jLength)
    {
        float i = 0.0f;

        while (i < 1.0f)
        {
            if (stop == false)
            {
                if (GameObject.Find("RecMan").GetComponent<RecManager>().playtransfcheck == false && playtransfcheckthis == true)
                {
                    i = i + rate;
                }
                else
                {
                        if ((Vector3.Distance(this.transform.position, end) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdpos || Quaternion.Angle(this.transform.rotation, endq) > GameObject.Find("RecMan").GetComponent<RecManager>().thresholdrot) && (this.Moving == true))
                        {
                            i = i + rate;
                            this.gameObject.transform.Find("cube").position = Vector3.Lerp(sourcepos, targetpos, i);// -(((this.transform.position)/145)*100);
                            this.gameObject.transform.Find("cube").rotation = (Quaternion.Slerp(sourcerot, targetrot, i));
                      }

                    else
                    {
                        i = i + rate;
                    }
                }
                yield return new WaitForEndOfFrame();
            }

            else
            {
                i = 1.0f;
            }
        }
        yield return null;
        print("Moveobjcomplete di objID=" + objID);
    }

    IEnumerator dodownloadprocedure(int procnumb)
    {
```

```
        yield return StartCoroutine(downloadprocedure(procnumb));
        playready = true;
    }

    IEnumerator downloadprocedure(int procednumb)
    {
        WWWForm formdown = new WWWForm();
        formdown.AddField("procnumber", procednumb);
        formdown.AddField("objectID", objID);

        WWW ObjallData = new WWW("http://" + IPaddressfinal + "/FARP/VirtualObjDataall.php", formdown);
        //note data all returns only recID1 - 1 should be a parameter
        yield return ObjallData;
        string ObjallDataString = ObjallData.text;
        Objall = ObjallDataString.Split(';');
        print("objall length=" + Objall.Length);

        for (int j = 0; j < (Objall.Length - 1); j++)
        {
            Objallsplit = Objall[j].Split('|');

            pttp[0, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[0], "timID:"));
            pttp[1, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[1], "objID:"));
            pttp[2, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[2], "recID:"));
            pttp[3, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[3], "x:"));
            pttp[4, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[4], "y:"));
            pttp[5, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[5], "z:"));
            pttp[6, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[6], "rotx:"));
            pttp[7, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[7], "roty:"));
            pttp[8, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[8], "rotz:"));
            pttp[9, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[9], "scalex:"));
            pttp[10, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[10], "scaley:"));
            pttp[11, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[11], "scalez:"));
            pttp[12, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[12], "rotquatx:"));
            pttp[13, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[13], "rotquaty:"));
            pttp[14, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[14], "rotquatz:"));
            pttp[15, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[15],
```

```
                "rotquatw:"));
        }
        yield return null;
    }

    string GetDataValue(string data, string index)
    {
        string value = data.Substring(data.IndexOf(index) + index.Length);
        if (value.Contains("|")) value = value.Remove(value.IndexOf('|'));
        return value;
    }

    IEnumerator douploadprocedure()
    {
        GameObject.Find("RecMan").GetComponent<RecManager>().Play.gameObject.SetActive(false);
        GameObject.Find("RecMan").GetComponent<RecManager>().Record.gameObject.SetActive(false);
        GameObject.Find("RecMan").GetComponent<RecManager>().ServerSet.gameObject.SetActive(false);
        GameObject.Find("RecMan").GetComponent<RecManager>().RemoteAssistance.gameObject.SetActive(false);

        yield return StartCoroutine(uploadprocedure());

        GameObject.Find("RecMan").GetComponent<RecManager>().Play.gameObject.SetActive(true);
        GameObject.Find("RecMan").GetComponent<RecManager>().Record.gameObject.SetActive(true);
        GameObject.Find("RecMan").GetComponent<RecManager>().ServerSet.gameObject.SetActive(true);
        GameObject.Find("RecMan").GetComponent<RecManager>().RemoteAssistance.gameObject.SetActive(true);
   }

    IEnumerator uploadprocedure()
    {
        GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure";
        print("partita upload di=" + objID);
        WWWForm form = new WWWForm();
        form.AddField("pttstrPost", pttstr);
        form.AddField("jjjPost", jjj);
        WWW www = new WWW(CreateObjDataUrl, form);
        yield return www;
        string wwwstring = www.text;
      if (wwwstring != "Upload Completed")
            //check connectivity while saving procedure on db.
        {
            print("connection Lost");
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure - Connection Lost - Reconnecting";
            uploadprocedure();
```

```
        }

        else
        {
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure - Completed";
            yield return new WaitForSecondsRealtime(3);
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "";
            yield return null;
            print("finito upload di=" + objID);
        }

        pttstr = null;
    }

    public void buildprocedure(string timID, string objID, string recID, string x, string y, string z, string rotx, string roty, string rotz, string scalex, string scaley, string scalez, string rotquatx, string rotquaty, string rotquatz, string rotquatw, int jj)
    {
        dtt[0] = timID;
        dtt[1] = objID;
        dtt[2] = recID;
        dtt[3] = x;
        dtt[4] = y;
        dtt[5] = z;
        dtt[6] = rotx;
        dtt[7] = roty;
        dtt[8] = rotz;
        dtt[9] = scalex;
        dtt[10] = scaley;
        dtt[11] = scalez;
        dtt[12] = rotquatx;
        dtt[13] = rotquaty;
        dtt[14] = rotquatz;
        dtt[15] = rotquatw;

        int j = jj - 1;

        if (j < 3599)
        {
            if (j > 0)
            {
                pttstr = pttstr + "~";
            }


            for (int i = 0; i < 16; i++)
            {
                pttstr = pttstr + dtt[i] + ";";
            }
        }
```

```
        else
        {
            print("Preocedure is too long");
        }
    }

    public void movbool()
    {
        if (this.Moving)
        {
        this.Moving = false;
        }

        else {
            this.Moving = true;
        }
    }

    public void realCreateObjDof(string timID, string objID, string recID,
      string x, string y, string z, string rotx, string roty, string rotz,
      string scalex, string scaley, string scalez, string rotquatx, string
      rotquaty, string rotquatz, string rotquatw)
    {
        WWWForm form = new WWWForm();

        form.AddField("timIDPost", timID);
        form.AddField("objIDPost", objID);
        form.AddField("recIDPost", recID);

        form.AddField("xPost", x);
        form.AddField("yPost", y);
        form.AddField("zPost", z);

        form.AddField("rotxPost", rotx);
        form.AddField("rotyPost", roty);
        form.AddField("rotzPost", rotz);

        form.AddField("scalexPost", scalex);
        form.AddField("scaleyPost", scaley);
        form.AddField("scalezPost", scalez);

        form.AddField("rotquatxPost", rotquatx);
        form.AddField("rotquatyPost", rotquaty);
        form.AddField("rotquatzPost", rotquatz);
        form.AddField("rotquatwPost", rotquatw);

        WWW www = new WWW(CreateObjDataUrl, form);
    }
}
```

C.2.2 Real Object Position (C#)


```
using UnityEngine;
using System.Collections;
using Vuforia;
using UnityEngine.UI;

//This script is utilised for sending to the remote assistante the position and orientations of the remote
//real components of the assembly.

//This script send information to the real object database.

//this script is attached to each the real components game object.

public class RealObjPos : MonoBehaviour
{
    //private ObjectTargetBehaviour mObjectTargetBehaviour = null;
    private ImageTargetBehaviour mImageTargetBehaviour = null;
    private ObjectTargetBehaviour mObjectTargetBehaviour = null;

    public int objID;
    public string objectID;
    //public int objType;//1 for images and 2 for objects targets behaviours

    public int rID; //int recordID to tecord the task number or record number
    public string recordID;

    public int tID;
    public string timeID;

    public bool recording;
    public bool store;
    public bool upload;
    public int jjj;

    public bool play;
    public bool playready;
    public int procedurenumber;

    public bool playtransfcheckthis;
    public int counterjplay;
    public bool stop;

    public string objx;
    public string objy;
    public string objz;

    public string objrotx;
    public string objroty;
    public string objrotz;

    public string objrotquatw;
    public string objrotquatx;
    public string objrotquaty;
```

```
        public string objrotquatz;

        public string objscalex;
        public string objscaley;
        public string objscalez;

        private string[] dtt = new string[16];  //single transform in time
        //private string[,] ptt = new string[16, 3600]; //array of transforms. each row is one dtt.
        private string pttstr;

        private float[,,] pttp = new float[16, 3600, 5]; //array of transforms. downloaded for play
        public string[] Objall;
        public string[] Objallsplit;

        public string teststring;
        public string indexx;

        static public string IPaddressfinal;
        string CreateObjDataUrl;

        private Vector3 butransfpos;
        private Quaternion butransfrot;

        private Vector3 butransflocpos;
        private Quaternion butransflocrot;

        private Vector3 bucubetransfpos;
        private Quaternion bucubetransfrot;

        private Vector3 bucubetransflocpos;
        private Quaternion bucubetransflocrot;

        private Vector3 st;
        private Vector3 end;
        private Quaternion stq;
        private Quaternion endq;
        public float speed = 100F;
        private float startTime;
        private float journeyLength;

        public Vector3 a;
        public Vector3 b;
        public Vector3 c;
        public float distance;

        public Vector3 t1;
        public Vector3 t2;
        public float tdiff;

        public float rate;
        public float burate;
```

```
    //public REAL;
    int igetrp;

    public float realx;
    public float realy;
    public float realz;
    public Vector3 realpos;

    public float realrotx;
    public float realroty;
    public float realrotz;
    public float realrotw;
    public Quaternion realrot;

    void Start()
    {
        IPaddressfinal = PlayerPrefs.GetString("IPfinale");
        CreateObjDataUrl = "http://" + IPaddressfinal + "/FARP/
          ObjDataRec.php";

        playtransfcheckthis = false;

        upload = false;
        play = false;
        playready = false;
        //procedurenumber = 2;
        counterjplay = 0;
        igetrp = 0;
    }

    void Update()
    {
        igetrp = igetrp + 1;

        if (igetrp == 5)
        {
            StartCoroutine(getrealpos());
            igetrp = 0;
        }
            realpos.x = realx;
            realpos.y = realy;
            realpos.z = realz;
            this.transform.position = realpos;
        realrot.x = realrotx;
        realrot.y = realroty;
        realrot.z = realrotz;
        realrot.w = realrotw;
        this.transform.rotation = realrot;

        if (recording)
            {

```

```
            }

            if (upload)
            {

            }

            if (play)
            {

            }

            if (playready)
            {

            }

            else
            {

            }
    }

    IEnumerator getrealpos()
    {
        WWWForm formdown = new WWWForm();
         //formdown.AddField("procnumber", procednumb);
         formdown.AddField("objectID", objID);

         WWW ObjallData = new WWW("http://" + IPaddressfinal + "/FARP/realObjDataalllast.php", formdown); //note data all returns only recID1 - 1 should be a parameter
         yield return ObjallData;
         string ObjallDataString = ObjallData.text;

         Objall = ObjallDataString.Split(';');
        //print("objall length=" + Objall.Length);
         for (int j = 0; j < (Objall.Length - 1); j++)
         {
             Objallsplit = Objall[j].Split('|');

             realx = float.Parse(GetDataValue(Objallsplit[3], "x:"));
             realy = float.Parse(GetDataValue(Objallsplit[4], "y:"));
             realz = float.Parse(GetDataValue(Objallsplit[5], "z:"));
            // pttp[10, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[10], "scaley:"));
            // pttp[11, j, objID - 1] = float.Parse(GetDataValue(Objallsplit[11], "scalez:"));
            realrotx = float.Parse(GetDataValue(Objallsplit[12], "rotquatx:"));
            realroty = float.Parse(GetDataValue(Objallsplit[13], "rotquaty:"));
            realrotz = float.Parse(GetDataValue(Objallsplit[14], "rotquatz:"));
            realrotw = float.Parse(GetDataValue(Objallsplit[15], "rotquatw:"));
         }
```

```
            yield return null;
        }

        string GetDataValue(string data, string index)
        {
            string value = data.Substring(data.IndexOf(index) + index.Length);
            if (value.Contains("|")) value = value.Remove(value.IndexOf('|'));
            return value;
        }
    }
```

C.2.3 Virtual Manipulation Object (C#)

...tbc)\FARPREMV0\Assets\Scripts\VirtualManipulationObj.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
//This script allows the assistant to modify the positions of the virtual objects (maniobj)
//through the utilisation of a virtual tool (tool)

//this script utilises the relations between the virtual objects overimposed over the real ones
//as triggers for grabbing and movingvirtual objects.

//virtObjRecords will thens save thre transformations and send them to the remote mantainer.
public class VirtualManipulationObj : MonoBehaviour
{
    public Material GreenMaterial;
    public Material bumaterial;
    public GameObject tool;
    // public GameObject centercgo;
    public GameObject maniobj;
    public bool toolVBon;
    // public bool toolVBtrigger;
    public int btntrigger; //used for trigging ditance when btn pressed
    public GameObject VirtRealObj;
    public bool manibool;
    //public Vector3 butooltipposVB;
    public Vector3 distancetest;
    public Vector3 distancezero;
    public Quaternion distanceangle;
    //bu local position pivot
    public Vector3 bulocalpospivot;
    public Quaternion bulocalrotpivot;
    public GameObject recman; //memory
    // Use this for initialization

    void Start()
    {
       toolVBon = false;
        btntrigger = 0;
        manibool = true;
        bulocalpospivot = this.gameObject.transform.localPosition;
        bulocalrotpivot = this.gameObject.transform.localRotation;
    }

    void Update()
    {
        toolVBon = GameObject.Find("VB").GetComponent<grabbtn>().pressbool;
       if (toolVBon)
        {
            btntrigger = btntrigger + 1;
            if (btntrigger == 1)
            {
                distancetest = tool.transform.position -
```

```
                    this.gameObject.transform.position;
                    distanceangle = tool.transform.rotation * this.gameObject.transform.localRotation;

                }
            }
            else
            {
                btntrigger = 0;
            }
        }

        private void OnTriggerEnter(Collider tool)
        {
            if (tool.gameObject.name == "toolbu")
            {
                this.GetComponent<Renderer>().material = GreenMaterial;
                print("tool colliding");
            }
        }

    //When the virtual component of the assembly (maniobj) and the tool (tool) collide
    //and the vurtual button (toolVBon) is pressed. The transform of the virtual component of the assembly
    //attaches to the virtual tool ones. Therefore, moving the virtual tool, the virtual compponente will
    //move as well. VirtObjRec will record it.
        void OnTriggerStay(Collider tool)
        {
            if (tool.gameObject.name == "toolbu")
            {
                print("tool colliding stay");
               recman.GetComponent<RecManager>().allfalse();

                if (toolVBon)
                {
                   if (manibool == true)
                    {
                        maniobj.transform.position = this.transform.position;
                        maniobj.transform.rotation = this.transform.localRotation;
                      if (Vector3.Distance(maniobj.transform.position, this.transform.position) < 0.5)
                        {
                            if (Quaternion.Angle(maniobj.transform.rotation, this.transform.localRotation) < 0.1)
                            {
                                manibool = false;
                           }
                        }
                        print("quiii ");
                    }

```

```
                else
                {
                    maniobj.transform.position = tool.transform.position - distancetest;
                    maniobj.transform.localRotation = tool.transform.rotation * Quaternion.Inverse(distanceangle);
                    print("quiii 2");
                }
            }

            else
            {
                this.transform.localPosition = bulocalpospivot;
                this.transform.localRotation = bulocalrotpivot;
            }
        }
    }


    void OnTriggerExit(Collider tool)
    {
        if (tool.gameObject.name == "toolbu")
        {
            this.GetComponent<Renderer>().material = bumaterial;
            recman.GetComponent<RecManager>().alltrue();
        }

    }
}

```

C.2.4 Grab button (C#)

...\LAST FARP RA (tbc)\FARPREMV0\Assets\Scripts\grabbtn.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using Vuforia;
using UnityEngine.UI;

//this script is attached to the vierual tool and manages the grabbing and release of virtual objects.
public class grabbtn : MonoBehaviour , IVirtualButtonEventHandler {

    public GameObject vbButtonObject;
    public GameObject tool;
    public Text grbtxt;
    public Vector3 butooltippos;
    //private int presscount;
    public bool pressbool;
    //public pressboolbool simulating button
    public bool pressboolbool;
    public Material pressedmat;
    public Material nonpressedmat;
    public GameObject recman;
    // Use this for initialization

    void Start () {
        vbButtonObject.GetComponent<VirtualButtonBehaviour>().RegisterEventHandler(this);
        //presscount = 0;
        pressbool = false;
       // triggerbtn = false;
        grbtxt.text = "Grab";
    }

    private void Update()
    {
        if (pressbool) {
            tool.GetComponentInChildren<Renderer>().material = pressedmat;
        }
        else {
            tool.GetComponentInChildren<Renderer>().material = nonpressedmat;
        }

        if (pressboolbool)
        {
            if (pressbool)
            {
                pressbool = false;
                recman.GetComponent<RecManager>().kfunct();
                grbtxt.text = "Grab";
            }
            else
            {
                pressbool = true;
                recman.GetComponent<RecManager>().kfunct();
```

```
                grbtxt.text = "Release";
            }
            pressboolbool = false;
        }
    }

    public void grab()
    {
        pressboolbool = true;
    }

    public void OnButtonPressed (VirtualButtonAbstractBehaviour vb)
    {
        if (pressbool) {
            pressbool = false;
            recman.GetComponent<RecManager>().kfunct();
        }
        else { pressbool = true;
        recman.GetComponent<RecManager>().kfunct();
        }
    }

    public void OnButtonReleased(VirtualButtonAbstractBehaviour vb)
    {

    }
}
```

C.2.5 Virtual Object Record (C#)


```
using UnityEngine;
using System.Collections;
using Vuforia;
using UnityEngine.UI;

//This script allows recording the virtual object transform modified through the virtual manipulator.
//The transforms suggested by the assistant are saved on the virtualobj database.

//this script is attached to each object.

public class VirtObjRecord : MonoBehaviour
{
    //private ObjectTargetBehaviour mObjectTargetBehaviour = null;
    private ImageTargetBehaviour mImageTargetBehaviour = null;
    private ObjectTargetBehaviour mObjectTargetBehaviour = null;

    public int objID;
    public string objectID;
    public int objType;//1 for images and 2 for objects targets behaviours

    public bool cancelup;

    public int rID; //int recordID to tecord the task number or record number
    public string recordID;

    public int tID;
    public string timeID;

    public bool recording;
    public bool store;
    public bool upload;
    public int localupload;

    public int jjj;

    public bool play;
    public bool playready;
    public int procedurenumber;

    public bool playtransfcheckthis;

    public int counterjplay;

    public bool stop;

    public string objx;
    public string objy;
    public string objz;

    public string objrotx;
    public string objroty;
```

```
    public string objrotz;


    public string objrotquatw;
    public string objrotquatx;
    public string objrotquaty;
    public string objrotquatz;

    public string objscalex;
    public string objscaley;
    public string objscalez;

    private string[] dtt = new string[16];  //single transform in time
    //private string[,] ptt = new string[16, 3600]; //array of transforms. 
      each row is one dtt.
    public string pttstr;

    private float[, ,] pttp = new float[16, 3600, 5]; //array of transforms. 
      downloaded for play
    public string[] Objall;
    public string[] Objallsplit;

    public string teststring;
    public string indexx;

    static public string IPaddressfinal;
    string CreateObjDataUrl;

    private Vector3 butransfpos;
    private Quaternion butransfrot;

    private Vector3 butransflocpos;
    private Quaternion butransflocrot;

    private Vector3 bucubetransfpos;
    private Quaternion bucubetransfrot;

    private Vector3 bucubetransflocpos;
    private Quaternion bucubetransflocrot;

    private Vector3 st;
    private Vector3 end;
    private Quaternion stq;
    private Quaternion endq;
    public float speed = 100F;
    private float startTime;
    private float journeyLength;

    public Vector3 a;
    public Vector3 b;
    public Vector3 c;
    public float distance;

```

```
    public Vector3 t1;
    public Vector3 t2;
    public float tdiff;

    public float rate;
    public float burate;

    void Start()
    {
        IPaddressfinal = PlayerPrefs.GetString("IPfinale");
        CreateObjDataUrl = "http://" + IPaddressfinal + "/FARP/
          VirtualObjDataRec.php";

        cancelup = false;

        playtransfcheckthis = false;
        bucubetransflocpos = this.gameObject.transform.GetChild
          (0).localPosition;
        bucubetransflocrot = this.gameObject.transform.GetChild
          (0).localRotation;

        upload = false;
        play = false;
        playready = false;
        //procedurenumber = 2;
        counterjplay = 0;
        pttstr = null;
        localupload = 0;

    }

    void Update()
    {

        rID = GameObject.Find("RecMan").GetComponent<RecManager>().rID;
        tID = GameObject.Find("RecMan").GetComponent<RecManager>().tID;

        recording = GameObject.Find("RecMan").GetComponent<RecManager>
          ().recording;
        store = GameObject.Find("RecMan").GetComponent<RecManager>().store;
        upload = GameObject.Find("RecMan").GetComponent<RecManager>().upload;
        play = GameObject.Find("RecMan").GetComponent<RecManager>().play;
        stop = GameObject.Find("RecMan").GetComponent<RecManager>().stop;

        cancelup = GameObject.Find("RecMan").GetComponent<RecManager>
          ().cancelupman;

        jjj = GameObject.Find("RecMan").GetComponent<RecManager>().j;
        procedurenumber = GameObject.Find("RecMan").GetComponent<RecManager>
          ().procedurenumber;

        rate = GameObject.Find("RecMan").GetComponent<RecManager>().rate;
```

```
        Vector3 objpos = this.gameObject.transform.position;
        Vector3 objrot = this.gameObject.transform.rotation.eulerAngles;
        Vector3 objscale = this.gameObject.transform.lossyScale;
        Quaternion objrotquat = this.gameObject.transform.rotation;


        objx = objpos.x.ToString();
        objy = objpos.y.ToString();
        objz = objpos.z.ToString();

        objrotx = objrot.x.ToString();
        objroty = objrot.y.ToString();
        objrotz = objrot.z.ToString();

        objscalex = objscale.x.ToString();
        objscaley = objscale.x.ToString();
        objscalez = objscale.x.ToString();

        objrotquatx = objrotquat.x.ToString();
        objrotquaty = objrotquat.y.ToString();
        objrotquatz = objrotquat.z.ToString();
        objrotquatw = objrotquat.w.ToString();

        recordID = rID.ToString();
        objectID = objID.ToString();
        timeID = tID.ToString();

        if (recording)
        {

            if (store)
            {
                buildprocedure(timeID, objectID, recordID, objx, objy, objz, objrotx, objroty, objrotz, objscalex, objscaley, objscalez, objrotquatx, objrotquaty, objrotquatz, objrotquatw, jjj);
            }
        }

        if (upload)
        {
            localupload = localupload + 1;

            if (localupload == 1)
            {
                StartCoroutine(douploadprocedure());
            }
        }

        else {
            localupload = 0;
            }
    }
```

```

    string GetDataValue(string data, string index)
    {
        string value = data.Substring(data.IndexOf(index) + index.Length);
        if (value.Contains("|")) value = value.Remove(value.IndexOf('|'));
        return value;
    }

    IEnumerator douploadprocedure()
    {
      yield return StartCoroutine(uploadprocedure());
   }

    IEnumerator uploadprocedure()
    {
        if (!cancelup)
        {
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure";
            print("partita upload di=" + objID);

            WWWForm form = new WWWForm();

            form.AddField("pttstrPost", pttstr);
            form.AddField("jjjPost", jjj);
            WWW www = new WWW(CreateObjDataUrl, form);
            yield return www;
            string wwwstring = www.text;

            if (wwwstring != "Upload Completed") //check connectivity while saving procedure on db.
            {
                print("connection Lost");
                GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure - Connection Lost - Reconnecting";
                uploadprocedure();
            }

            else
            {
                GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "Uploading Procedure - Completed";
                yield return new WaitForSecondsRealtime(3);
                GameObject.Find("RecMan").GetComponent<RecManager>().messages.text = "";
                // GameObject.Find("RecMan").GetComponent<RecManager>().upload = false;
                yield return null;
                print("finito upload di=" + objID);
            }
            pttstr = null;
        }
```

```

        else
        {
            cancelup = false;
            yield return new WaitForSecondsRealtime(3);
            GameObject.Find("RecMan").GetComponent<RecManager>().messages.text 
              = "";
            GameObject.Find("RecMan").GetComponent<RecManager>().cancelupman = 
              false;
            //return null;
        }
    }

    public void buildprocedure(string timID, string objID, string recID, 
      string x, string y, string z, string rotx, string roty, string rotz, 
      string scalex, string scaley, string scalez, string rotquatx, string 
      rotquaty, string rotquatz, string rotquatw, int jj)
    {

        dtt[0] = timID;
        dtt[1] = objID;
        dtt[2] = recID;
        dtt[3] = x;
        dtt[4] = y;
        dtt[5] = z;
        dtt[6] = rotx;
        dtt[7] = roty;
        dtt[8] = rotz;
        dtt[9] = scalex;
        dtt[10] = scaley;
        dtt[11] = scalez;
        dtt[12] = rotquatx;
        dtt[13] = rotquaty;
        dtt[14] = rotquatz;
        dtt[15] = rotquatw;

        int j = jj - 1;

        if (j < 3599)
        {
            if (j > 0)
            {
                pttstr = pttstr + "~";
            }


            for (int i = 0; i < 16; i++)
            {
                //ptt[i, j] = dtt[i];
                pttstr = pttstr + dtt[i] + ";";
            }
        }

```

...FARP RA (tbc)\FARPREMV0\Assets\Scripts\VirtObjRecord.cs 7

```
        else
        {
            print("Preocedure is too long");
        }


    }


}


```

C.2.6 Real Object Data All (php)

```
<?php
//query for calling all realobject data related to procedur pn and object
 oID

     $pn = $_POST["procnumber"]; //"Lucas.Test AC";
     $oID = $_POST["objectID"]; //"Lucas.Test AC";

    //Make Connection
    $conn =
     mysqli_connect('89.46.111.46','Sql1112120','1r64275t1p','Sql1112120_5')
     ;
    //Check Connection
    if(!$conn){
        die("Connection Failed. ". mysqli_connect_error());
    }

    $sql = "SELECT timID, objID, recID, x, y, z, rotx, roty, rotz, scalex,
     scaley, scalez, rotquatx, rotquaty, rotquatz, rotquatw  FROM
     realobj6dof WHERE recID = '$pn' AND objID = '$oID' ORDER BY timID"; //
     AND objID = '$oID'
    $result = mysqli_query($conn ,$sql);
    echo $pn;

    if(mysqli_num_rows($result) > 0){
        //show data for each row

        while($row = mysqli_fetch_assoc($result)){
            echo "timID:".$row['timID'] ."|objID:".$row['objID'] ."|recID:".
             $row['recID'] ."|x:".$row['x'] ."|y:".$row['y'] ."|z:".
             $row['z'] ."|rotx:".$row['rotx'] ."|roty:".$row['roty'] ."|
             rotz:".$row['rotz'] ."|scalex:".$row['scalex'] ."|scaley:".
             $row['scaley'] ."|scalez:".$row['scalez'] ."|rotquatx:".
             $row['rotquatx'] ."|rotquaty:".$row['rotquaty'] ."|rotquatz:".
             $row['rotquatz'] ."|rotquatw:".$row['rotquatw'] . ";";
        }
    }

?>
```

C.2.7 Virtual Object Data All (php)

```
<?php
//query for calling all virtualobject data related to procedur pn and object oID

     $pn = $_POST["procnumber"]; //"Lucas.Test AC";
     $oID = $_POST["objectID"]; //"Lucas.Test AC";

    //Make Connection
$conn = mysqli_connect('89.46.111.46','Sql1112120','1r64275t1p','Sql1112120_5');
    //Check Connection
    if(!$conn){
        die("Connection Failed. ". mysqli_connect_error());
    }

    $sql = "SELECT timID, objID, recID, x, y, z, rotx, roty, rotz, scalex, scaley,
    scalez, rotquatx, rotquaty, rotquatz, rotquatw  FROM virtualobj6dof WHERE recID
    = '$pn' AND objID = '$oID' ORDER BY timID"; //AND objID = '$oID'
    $result = mysqli_query($conn ,$sql);
    echo $pn;

    if(mysqli_num_rows($result) > 0){
        //show data for each row

        while($row = mysqli_fetch_assoc($result)){
            echo "timID:".$row['timID'] ."|objID:".$row['objID']
            ."|recID:".$row['recID'] ."|x:".$row['x'] ."|y:".$row['y']
            ."|z:".$row['z'] ."|rotx:".$row['rotx'] ."|roty:".$row['roty']
            ."|rotz:".$row['rotz'] ."|scalex:".$row['scalex']
            ."|scaley:".$row['scaley'] ."|scalez:".$row['scalez']
            ."|rotquatx:".$row['rotquatx'] ."|rotquaty:".$row['rotquaty']
            ."|rotquatz:".$row['rotquatz'] ."|rotquatw:".$row['rotquatw'] . ";";
        }
    }

?>
```

C.3 ARRA Test ANOVA

The table reported in this section contains the dataset gathered throughout ARRA's validation tests and utilised for the statistical analysis in SPSS.

The table is structured as follows:

The first column reports the assistance method: Video-call Vs. AR

The second column reports the Operation Id: 1-8 because 8 tasks. 4 assemblies and 4 disassembles.

The third column reports the spatial referencing error registered by the observer of the test. The values can be: Correct, Opposite, Other.

The fourth column reports in what kind of action the observed recorded the spatial referencing error: in an identification action, in a directional action or in a coupling action. More details about these actions are explained in Section 5.4.2.

The last column divides the operations in assembly and disassembly tasks. Operation 1-4 are assembly (A). Operations 5-8 are disassembling (B).

The number of rows is 450 as explained in Section 5.5.

Table C.1 ARRA's validation dataset.

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
Video	1	Correct	Identification	A
Video	1	Opposite	Identification	A
Video	1	Correct	Identification	A
Video	1	Correct	Identification	A
Video	1	Opposite	Identification	A
Video	1	Other	Identification	A
Video	1	Correct	Identification	A
Video	1	Correct	Identification	A
Video	1	Opposite	Identification	A
Video	1	Opposite	Identification	A
Video	1	Opposite	Identification	A
Video	1	Correct	Identification	A
Video	2	Opposite	Identification	A
Video	2	Correct	Identification	A
Video	2	Opposite	Identification	A
Video	2	Correct	Identification	A
Video	2	Correct	Identification	A
Video	2	Other	Identification	A
Video	2	Correct	Identification	A
Video	2	Opposite	Identification	A
Video	2	Correct	Identification	A
Video	2	Opposite	Identification	A
Video	2	Correct	Identification	A
Video	2	Opposite	Identification	A
Video	3	Correct	Identification	A
Video	3	Correct	Identification	A
Video	3	Opposite	Identification	A
Video	3	Correct	Identification	A
Video	3	Correct	Identification	A
Video	3	Other	Identification	A
Video	3	Other	Identification	A
Video	3	Opposite	Identification	A
Video	3	Opposite	Identification	A
Video	3	Correct	Identification	A
Video	3	Opposite	Identification	A
Video	4	Opposite	Identification	A

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
Video	4	Correct	Identification	A
Video	4	Correct	Identification	A
Video	4	Correct	Identification	A
Video	4	Opposite	Identification	A
Video	4	Correct	Identification	A
Video	4	Correct	Identification	A
Video	4	Opposite	Identification	A
Video	4	Correct	Identification	A
Video	4	Opposite	Identification	A
Video	4	Correct	Identification	A
Video	1	Correct	Direction	A
Video	1	Opposite	Direction	A
Video	1	Correct	Direction	A
Video	1	Correct	Direction	A
Video	1	Opposite	Direction	A
Video	1	Opposite	Direction	A
Video	1	Correct	Direction	A
Video	1	Opposite	Direction	A
Video	1	Correct	Direction	A
Video	1	Opposite	Direction	A
Video	1	Correct	Direction	A
Video	1	Correct	Direction	A
Video	2	Other	Direction	A
Video	2	Correct	Direction	A
Video	2	Correct	Direction	A
Video	2	Opposite	Direction	A
Video	2	Correct	Direction	A
Video	2	Correct	Direction	A
Video	2	Opposite	Direction	A
Video	2	Correct	Direction	A
Video	2	Other	Direction	A
Video	2	Correct	Direction	A
Video	2	Correct	Direction	A
Video	2	Opposite	Direction	A
Video	3	Correct	Direction	A
Video	3	Correct	Direction	A
Video	3	Correct	Direction	A
Video	3	Opposite	Direction	A
Video	3	Correct	Direction	A
Video	3	Other	Direction	A
Video	3	Opposite	Direction	A
Video	3	Correct	Direction	A
Video	3	Correct	Direction	A

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
Video	3	Correct	Direction	A
Video	3	Correct	Direction	A
Video	4	Correct	Direction	A
Video	4	Correct	Direction	A
Video	4	Correct	Direction	A
Video	4	Correct	Direction	A
Video	4	Other	Direction	A
Video	4	Correct	Direction	A
Video	4	Correct	Direction	A
Video	4	Correct	Direction	A
Video	4	Opposite	Direction	A
Video	4	Opposite	Direction	A
Video	4	Correct	Direction	A
Video	5	Correct	Identification	B
Video	5	Other	Identification	B
Video	5	Correct	Identification	B
Video	5	Correct	Identification	B
Video	5	Other	Identification	B
Video	5	Other	Identification	B
Video	5	Other	Identification	B
Video	5	Correct	Identification	B
Video	5	Correct	Identification	B
Video	5	Opposite	Identification	B
Video	5	Correct	Identification	B
Video	6	Correct	Identification	B
Video	6	Other	Identification	B
Video	6	Correct	Identification	B
Video	6	Other	Identification	B
Video	6	Correct	Identification	B
Video	6	Correct	Identification	B
Video	6	Other	Identification	B
Video	6	Other	Identification	B
Video	6	Other	Identification	B
Video	6	Correct	Identification	B
Video	6	Other	Identification	B
Video	7	Correct	Identification	B
Video	7	Correct	Identification	B
Video	7	Other	Identification	B
Video	7	Correct	Identification	B
Video	7	Correct	Identification	B
Video	7	Other	Identification	B
Video	7	Correct	Identification	B
Video	7	Other	Identification	B

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
Video	7	Other	Identification	B
Video	7	Correct	Identification	B
Video	7	Other	Identification	B
Video	8	Correct	Identification	B
Video	8	Correct	Identification	B
Video	8	Correct	Identification	B
Video	8	Correct	Identification	B
Video	8	Other	Identification	B
Video	8	Correct	Identification	B
Video	8	Correct	Identification	B
Video	8	Opposite	Identification	B
Video	8	Correct	Identification	B
Video	8	Correct	Identification	B
Video	8	Correct	Identification	B
Video	5	Correct	Coupling	B
Video	5	Opposite	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Opposite	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Correct	Coupling	B
Video	5	Correct	Coupling	B
Video	6	Opposite	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Opposite	Coupling	B
Video	6	Correct	Coupling	B
Video	6	Correct	Coupling	B
Video	7	Correct	Coupling	B
Video	7	Other	Coupling	B
Video	7	Correct	Coupling	B
Video	7	Opposite	Coupling	B
Video	7	Correct	Coupling	B
Video	7	Correct	Coupling	B
Video	7	Correct	Coupling	B

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
Video	7	Correct	Coupling	B
Video	7	Correct	Coupling	B
Video	7	Correct	Coupling	B
Video	7	Opposite	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Other	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Opposite	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Correct	Coupling	B
Video	8	Opposite	Coupling	B
Video	8	Correct	Coupling	B
Video	5	Correct	Direction	B
Video	5	Opposite	Direction	B
Video	5	Correct	Direction	B
Video	5	Other	Direction	B
Video	5	Correct	Direction	B
Video	5	Correct	Direction	B
Video	5	Correct	Direction	B
Video	5	Opposite	Direction	B
Video	5	Correct	Direction	B
Video	5	Other	Direction	B
Video	5	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	6	Correct	Direction	B
Video	7	Correct	Direction	B
Video	7	Correct	Direction	B
Video	7	Other	Direction	B
Video	7	Correct	Direction	B
Video	7	Correct	Direction	B
Video	7	Opposite	Direction	B

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
Video	7	Correct	Direction	B
Video	7	Correct	Direction	B
Video	7	Correct	Direction	B
Video	7	Other	Direction	B
Video	7	Opposite	Direction	B
Video	8	Correct	Direction	B
Video	8	Opposite	Direction	B
Video	8	Correct	Direction	B
Video	8	Correct	Direction	B
Video	8	Correct	Direction	B
Video	8	Correct	Direction	B
Video	8	Other	Direction	B
Video	8	Opposite	Direction	B
Video	8	Correct	Direction	B
Video	8	Correct	Direction	B
Video	8	Correct	Direction	B
ARRA	1	Correct	Identification	A
ARRA	1	Correct	Identification	A
ARRA	1	Correct	Identification	A
ARRA	1	Correct	Identification	A
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ARRA	1	Correct	Identification	A
ARRA	1	Correct	Identification	A
ARRA	2	Correct	Identification	A
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ARRA	2	Correct	Identification	A
ARRA	2	Correct	Identification	A
ARRA	2	Correct	Identification	A
ARRA	3	Correct	Identification	A
ARRA	3	Correct	Identification	A
ARRA	3	Correct	Identification	A

Assistance	Operation	SpatialRef	ErrorKind	OperationAB
ARRA	3	Correct	Identification	A
ARRA	3	Correct	Identification	A
ARRA	3	Correct	Identification	A
ARRA	3	Correct	Identification	A
ARRA	3	Correct	Identification	A
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ARRA	4	Correct	Identification	A
ARRA	4	Correct	Identification	A
ARRA	4	Correct	Identification	A
ARRA	1	Correct	Direction	A
ARRA	1	Correct	Direction	A
ARRA	1	Correct	Direction	A
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ARRA	1	Correct	Direction	A
ARRA	1	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Other	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Other	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A
ARRA	2	Correct	Direction	A

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
ARRA	3	Correct	Direction	A
ARRA	3	Correct	Direction	A
ARRA	3	Correct	Direction	A
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ARRA	3	Correct	Direction	A
ARRA	3	Correct	Direction	A
ARRA	3	Correct	Direction	A
ARRA	3	Correct	Direction	A
ARRA	3	Correct	Direction	A
ARRA	4	Correct	Direction	A
ARRA	4	Correct	Direction	A
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ARRA	4	Correct	Direction	A
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ARRA	4	Correct	Direction	A
ARRA	4	Correct	Direction	A
ARRA	5	Correct	Identification	B
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ARRA	6	Correct	Identification	B
ARRA	6	Correct	Identification	B
ARRA	6	Correct	Identification	B
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ARRA	6	Correct	Identification	B
ARRA	6	Correct	Identification	B

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
ARRA	6	Correct	Identification	B
ARRA	7	Correct	Identification	B
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ARRA	7	Correct	Identification	B
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ARRA	8	Correct	Identification	B
ARRA	8	Correct	Identification	B
ARRA	8	Correct	Identification	B
ARRA	8	Correct	Identification	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
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ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	5	Correct	Coupling	B
ARRA	6	Correct	Coupling	B
ARRA	6	Correct	Coupling	B
ARRA	6	Correct	Coupling	B
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ARRA	6	Correct	Coupling	B
ARRA	6	Correct	Coupling	B
ARRA	6	Correct	Coupling	B

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
ARRA	6	Correct	Coupling	B
ARRA	6	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	7	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
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ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	8	Correct	Coupling	B
ARRA	5	Correct	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Other	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Correct	Direction	B
ARRA	5	Other	Direction	B
ARRA	5	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Other	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Other	Direction	B

Assistance	*Operation*	*SpatialRef*	*ErrorKind*	*OperationAB*
ARRA	6	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	6	Correct	Direction	B
ARRA	7	Correct	Direction	B
ARRA	7	Correct	Direction	B
ARRA	7	Correct	Direction	B
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ARRA	7	Correct	Direction	B
ARRA	7	Correct	Direction	B
ARRA	7	Correct	Direction	B
ARRA	7	Correct	Direction	B
ARRA	7	Other	Direction	B
ARRA	7	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Other	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B
ARRA	8	Correct	Direction	B