Robotics and Computer–Integrated Manufacturing 49 (2018) 215–228

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Review

A systematic review of augmented reality applications in maintenance

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ARTICLE INFO

Keywords:
Augmented Reality
Tracking
Authoring
Digital engineering
Maintenance
Systematic literature review

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 paper, 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 paper 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.

1. Introduction

Milgramt and Kishinott [1] define Augmented Reality as a way to "augment" the real-world with virtual objects. More specifically Azuma et al. [2] 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 [3,4]. Its application in the maintenance field has shown several advantages at an academic level.

By maintenance is meant 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 [5].

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 paper 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 authors 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 [6]. This approach is particularly relevant for researches currently experiencing a fast development.

This paper is organized in four sections. Section 1 introduces the project. Section 2 reports on the methodology utilised for this SLR. Section 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 4 reports conclusions and future works.

2. 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 et al. in "systematic approaches to a successful literature review" [7]. 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

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http://dx.doi.org/10.1016/j.rcim.2017.06.002
Received 29 March 2017; Received in revised form 6 June 2017; Accepted 27 June 2017
Available online 11 July 2017
0736-5845/

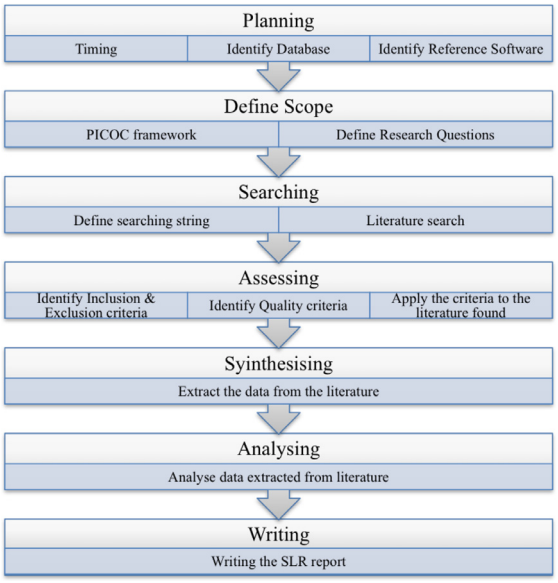

Fig. 1. SLR methodology utilised for this SLR [7]. In each one of the 7 rectangles are reported each step name (on the top) and its outcomes (on the bottom).

rectangles) and the outcomes of each step (blue rectangles) are outlined in Fig. 1.

2.1. Step 1 - planning

The planning phase is the very initial step to carry out a SLR. As described in Fig. 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 [8] 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 [7].

The reference manager software utilised is Mendely (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. Step 2 - defining the scope

Defining the scope actualizes 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 [7]. As a result of i and ii, different review and key papers on AR have been identified [9–14]. Then the PICOC framework has been utilised to define the key concepts of the research [7]. 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 utilization 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 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?

Table 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

2.3. Step 3 - Searching

The Searching step consists of browsing separately the databases identified at step 1 and listed in Section 2.1 utilising the string: ("Augmented Reality") AND ("Maintenance"). It has been selected based on the research questions and key concepts stated in Section 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. Table 1.

Since this phase has been carried out for each database separately, the final number of 723 documents includes duplicates. More details are shown in Fig. 2.

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

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 utilized 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 authors' experience and takes inspiration from other successful literature studies [6–8];

These criteria have been applied to the documents found in the four databases listed in Section 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