Towards the next generation of advanced technical documentation in augmented reality: the case of MILL 4.0

Original Citation:
Towards the next generation of advanced technical documentation in augmented reality: the case of MILL 4.0 / Evangelista, Alessandro. - ELETTRONICO. - (2021). [10.60576/poliba/iris/evangelista-alessandro_phd2021]

Availability:
This version is available at http://hdl.handle.net/11589/225858 since: 2021-05-10

Published version
DOI:10.60576/poliba/iris/evangelista-alessandro_phd2021

Publisher: Politecnico di Bari

Politecnico
di Bari

Department of Mechanics, Mathematics and Management
MECHANICAL AND MANAGEMENT ENGINEERING Ph.D. Program
SSD: ING-IND/15 - DESIGN METHODS FOR INDUSTRIAL ENGINEERING

Final Dissertation

TOWARDS THE NEXT GENERATION OF ADVANCED TECHNICAL DOCUMENTATION IN AUGMENTED REALITY: THE CASE OF MILL 4.0

by

Evangelista Alessandro

Referees:

Prof. Francesco Ferrise
(Politecnico di Milano)

Prof. Fabio Bruno
(Università della Calabria)

Supervisor:

Prof. Antonio E. Uva

Coordinator of Ph.D Program:

Prof. Giuseppe P. Demelio

Course n°33, 19/02/2018-18/02/2021

to my beloved parents who have always believed in me.

Index

Abstract

Augmented Reality (AR) promises to create direct, automatic, and actionable links between the physical world and electronic information. It provides an immediate and straightforward user interface to an electronically enhanced physical world. In particular, Industrial AR allows the integration between knowledge-based information, traditionally used by operators and provided mainly in paper documentation and data available from sensors on equipment. This approach is suggested by companies, especially small and medium-sized enterprises, who want a gradual introduction of Industry 4.0 technologies within their established practices.

The scope of this work is to develop an advanced technical documentation system in AR for a flour milling plant. The work discussed in this dissertation aims to bring added value to the existing literature in the field of industrial AR and advanced technical documentation. Besides, an attempt will be made to shed light on the role of AR as an enabling technology for the industry of the future. First, we focused on different industrial AR interfaces in order to understand established practices to guide IAR interface design. Then, we investigated the AR key technology with a novel approach based on patent research. Finally, the main result of this work is the design and development of two AR systems for a flour milling plant that following two different design approaches.

Introduction

The scope of this work is to develop an advanced technical documentation system in Augmented Reality (AR) for a flour milling plant. The purpose of a flour milling plant is to process wheat, rice and corn into flour to create food products.

The work discussed in this dissertation aims to bring added value to the existing literature in the field of industrial AR and advanced technical documentation. In addition, an attempt will be made to shed light on the role of AR as an enabling technology for the industry of the future.

In recent decades, the number and the diversity of industrial products has increased, as well as the complexity of the machinery in industrial scenario. Additionally, Industry 4.0—that is the trend towards the informatization of industrial production—drives an exchange of a significant volume of technical information among machines, storage systems, production plants, and people [1]. One category of information associated with a product or device is technical documentation, including operation and maintenance manuals, operating instructions, and installation manuals [2]. This documentation consists of technical information that may describe a component, provide instructions for a task, data, and so on.

Most technical information assets are increasingly available in a wide variety of digital documents. They are usually conveyed through visual cues: video, text, image, CAD models, and so on. Consequently, the devices used to convey technical documentation are also evolving from traditional ones such as paper manuals and monitors to handheld devices and holographic displays. We believe that AR, as key enabling technology of Industry 4.0, will be employed in the visualization of these next-generation manuals.

AR combines digital information in the form of virtual objects (e.g., text, digital image, video, 3D model, audio, haptic and so on) with a real environment. AR also allows immediate access to information that is not naturally present in a real environment and integrates a virtual interface with the reality. The rationale behind AR is to embed the computing experience in the real world, thus making possible a paradigm shift from a traditional desktop interface to a world-centric interface. Therefore, AR aims to make the world our user interface [3].

AR is ascribed a great potential for many fields of application, including the industrial one. Despite this potential, AR is still not widely adopted in real-world industrial settings due to the complex requirements that AR applications face, as argued by Lorenz et al. [4]. They can have different origins: usability and user acceptance, technical, environmental, regulatory, or economic. As a result, we understand that it is paramount that research groups collaborate with industrial companies to develop systems that meet all of these requirements.

In this work, we approached AR technology from different aspects, both theoretical and implementational, emphasizing the industrial scenario of Mill 4.0. First, we tried to put in order on the various industrial AR interfaces present in the literature. In fact, we made a Systematic Literature Review of over 20 years of literature in Industrial Augmented Reality (IAR), useful to understand established practices to orientate in IAR interface design and to present future research directions. Then, we investigated user preferences about how to convey information in IAR interfaces to the user. We focused on the feedback from IAR potential technical writers documentation for assembly or maintenance operations. Moreover, we investigated the AR key technology with a novel approach based on patent research. We searched the USPTO for AR-related granted patents; we selected and manually browsed a total of 2,373, we classified them into five key technological classes and then, we analyzed the results. Finally, we developed two prototypes of advanced technical documentation that exploits AR as a means to transfer information to users of an industrial Mill 4.0 scenario.

In Chapter 1, we introduce the Industrial Augmented Reality (IAR) as one of the Industry 4.0 (I4.0) enabling technologies. We describe the AR technology and its application in the industrial scenario.

In Chapter 2, we present a systematic literature review of visualization methods for technical instructions in IAR prototypes and concepts for maintenance, assembly, and training procedures: a total of 348 visual assets analyzed, extracted from 122 selected papers published between 1997 to 2019. We propose a novel classification for IAR technical visual assets according to: what content is displayed via the visual asset, how the visual asset can convey information, and why the visual asset is used.

In Chapter 3, we present a work that aims to investigate user preferences about how to convey information in IAR interfaces to the user. This study gathers the preferences of 105 selected users that have knowledge about IAR issues, graphical user interfaces (GUI) designing, and assembly/maintenance procedures.

In Chapter 4, with the main purpose of choosing optimal technological solutions to be implemented in the Mill 4.0 scenario, we unveil the technological trends of the AR domain. Specifically, this work tries to explain the technological development of AR by revealing temporal trends, geographical distribution, and most involved organizations in AR patenting. To do so, we collected 2,373 AR granted patents filed between 1993 and 2018 at the USPTO.

In Chapter 5, we describe a prototype developed by us of AR application that augments a Piping and Instrumentation Diagram (P&ID) drawing of a flour milling plant, thus allowing operators to retrieve useful information for the maintenance procedure, as the location of equipment in the plant. We effectively tested the application in the scenario of a milling plant through a user study.

Finally, in Chapter 6, we describe a novel approach for the implementation of a context-aware technical information manager (CATIM) that acquires context data about activity, operator, and environment, and then based on these data, proposes a dynamic AR user interface tailored to the current operating context. We also provide our approach to the implementation of CATIM, and the first evaluation in a real Mill 4.0 scenario to better explain how the system works.

Chapter 1. AR as enabling Technology of Industry 4.0

1.1. Industrial Augmented Reality (IAR)

Augmented reality (AR) aims to convey information that is directly registered to the physical environment. In particular, in the industrial field, AR aspires to bridge real and virtual assets in support of complex maintenance and assembly procedures. An augmented scene is composed of three main components: (1) a real-world object (feature), (2) its projected location in the augmented scene (anchor), and (3) a virtual model associated with the real-world object (visual asset, Fig. 1). Industrial Augmented Reality (IAR) is particularly well-suited for technical communication since it affords spatial registration of information and instructions anchored with the real object.

Fig. 1 Three different visual assets that convey the same instruction in an IAR interface: an animated product model of a socket wrench (a), a static auxiliary model of an arrow (b), a text instruction (c).

In his 1997 survey paper [5], Azuma proposed the definition of AR, which is still the most accepted by the scientific community nowadays. Based on this definition, AR must have the following three characteristics: (i) combines real and virtual, (ii) Interactive in real-time, and (iii) registered in 3D.

To combine virtual and real stimuli, Azuma's definition of AR requires specific output devices, i.e., a **display device**. Moreover, the definition also requires spatial registration and interactivity; this means that virtual elements must be real-time precisely aligned with the real environment; the **tracking** system takes care of this aspect, dynamically determining the spatial properties of the virtual entities in a real environment. Finally, the Interactivity aspect also implies that an AR system needs a **user interaction** module capable of operating in conjunction with the tracking system.

Based on the analysis of Azuma's definition, three main technology can be identified:

The **display** includes visual displays and nonvisual displays. The essential requirement discriminating AR displays from ordinary computer displays consists in the necessity to merge reality and virtuality. This can be achieved both by using an Head-Mounted Display (HMD) optical see-through (see Fig. 2) or a Hand Held Display (HHD) video see-through (see Fig. 3) [6]. Another visual display solution consists of projecting a virtual object onto the physical object; this display technology is known as the Spatial AR [7] (see Fig. 4). Out of the visual domain, nonvisual displays are used for involving the remaining four human senses in AR experiences. Indeed, audio [8], haptic [9], olfactory and gustatory [10] displays complete the class of AR displays.

Fig. 2 An operator wears an HMD optical see-through display.

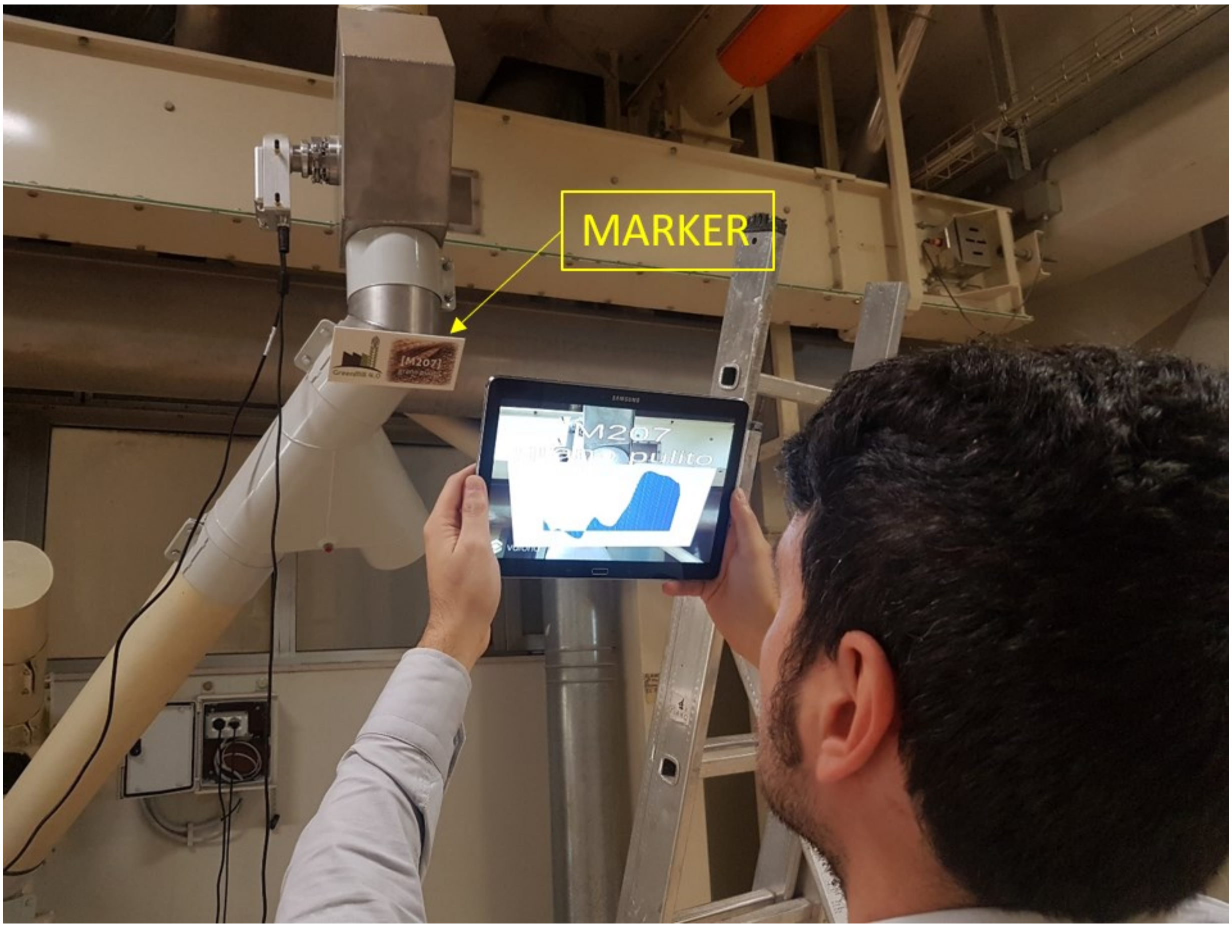


Fig. 3 An operator with a video see-through display, in particular a HHD (Tablet), framing a marker to augment the real scene.

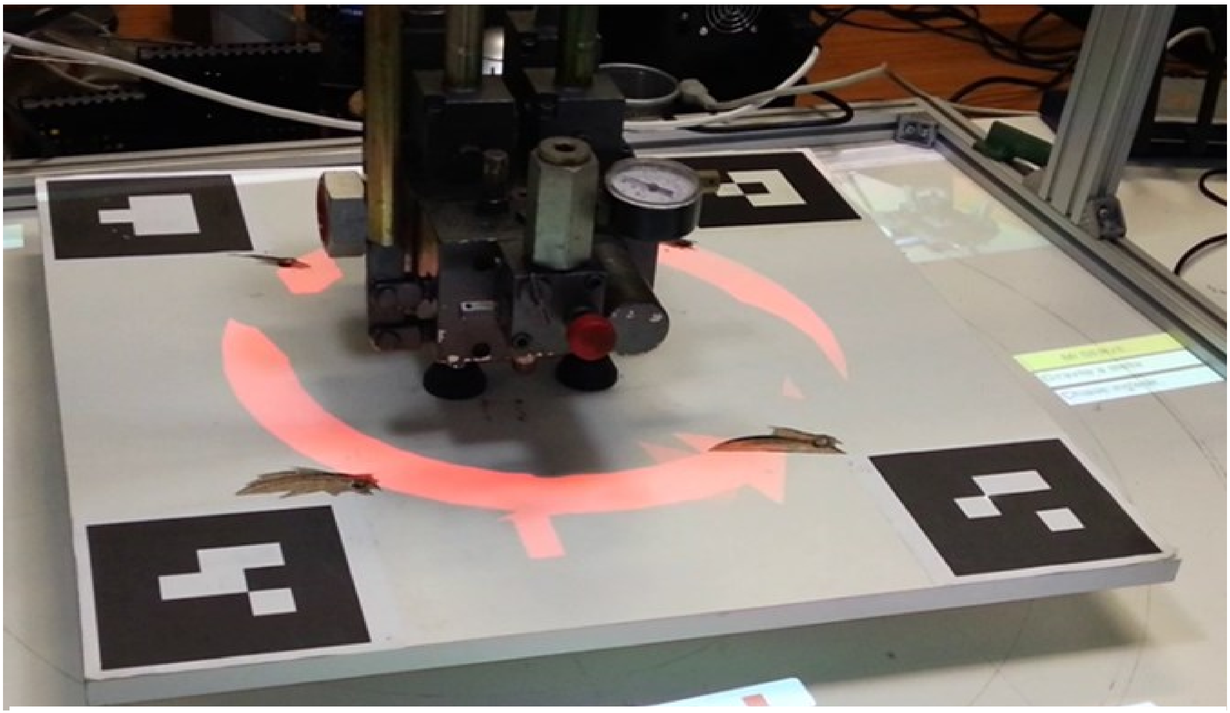


Fig. 4 Spatial Augmented Reality system for maintenance.

The **tracking** includes systems that perform the virtual object registration in a real environment; besides, in order to provide a compelling AR experience, virtual elements must be precisely aligned with the real environment in real-time. Therefore, AR tracking system is one of the main critical aspects of AR and is used to dynamically determine the spatial properties (6DOF) of the virtual entities in a real environment. Specifically, it combines hardware technology with a variety of sensors such as mechanical, electromagnetic, ultrasonic, optical tracking, and software algorithms for tracking the real environment [11]–[14]. Fig. 5 shows different types of tracking approaches.

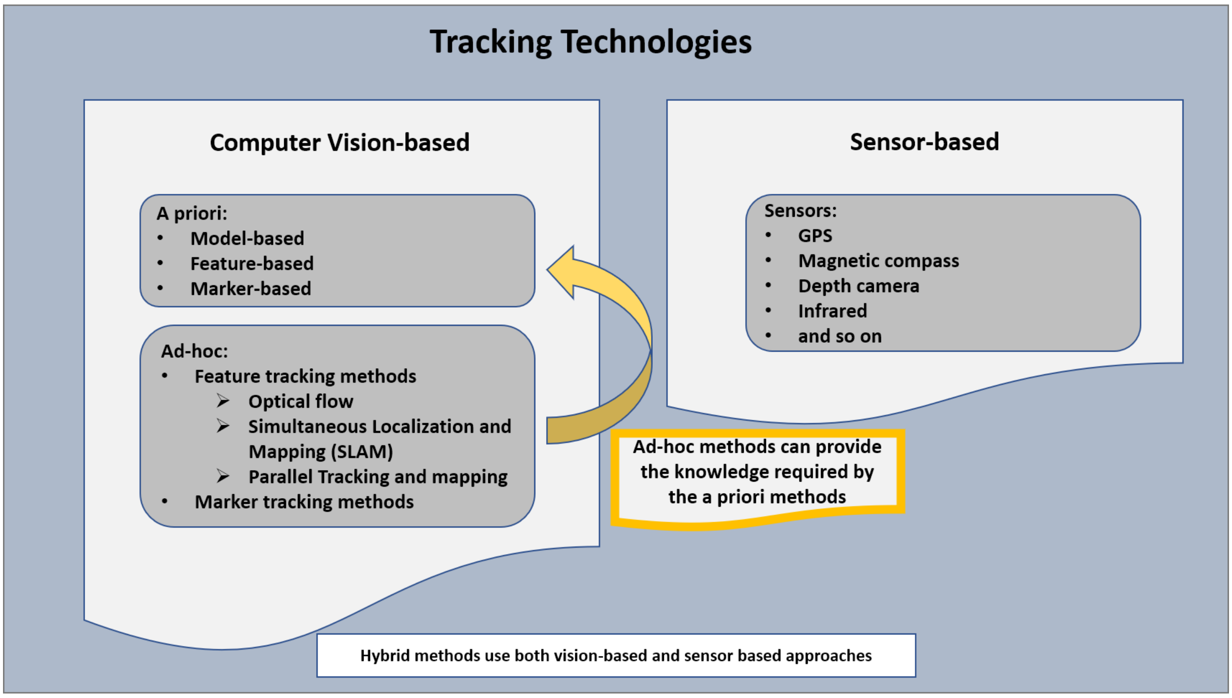


Fig. 5 Different technological approach to tracking.

The **user interface (UI)** includes a specific branch of HCI research, uses alternative means to traditional 2D UI such as a mouse, keyboard, and touch screen input. The AR uses instead non-desktop UI such as 3D input, speech, gestures (see Fig. 6), gaze, and so on [15]–[18]. In particular, interaction methods as information browsers, 3D UI, tangible UI, natural UI, and multimodal interface [19] .

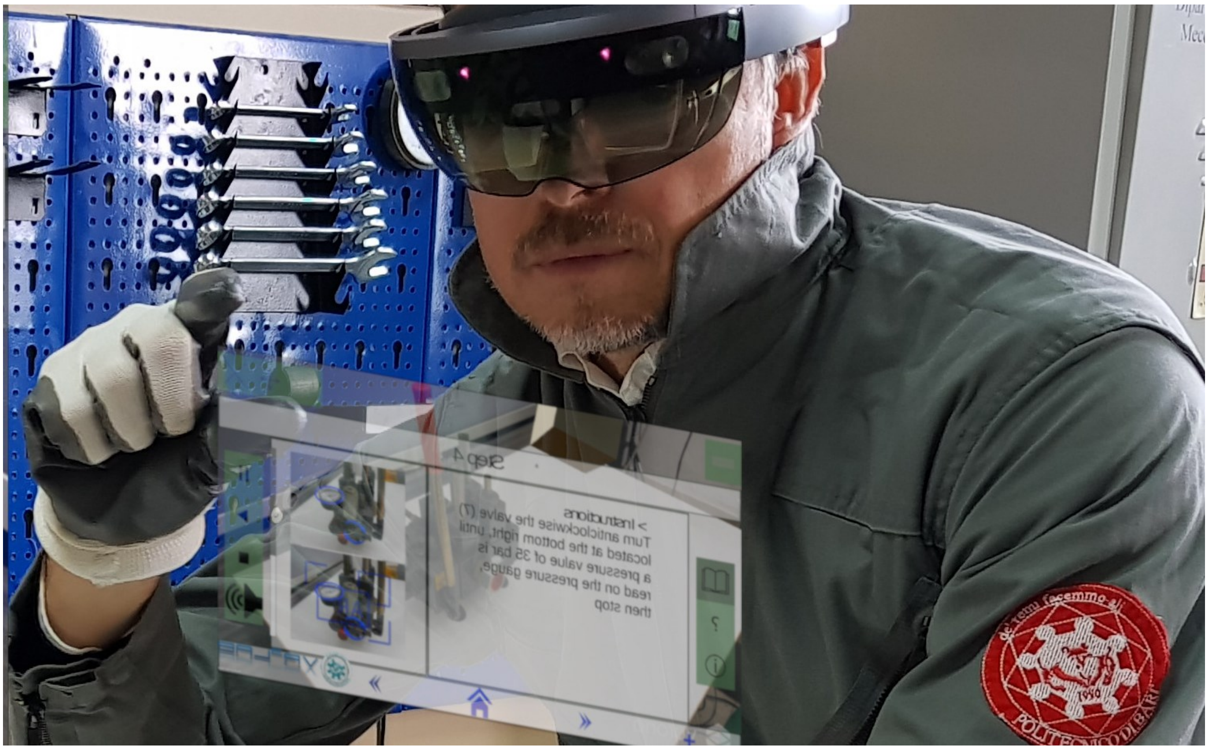


Fig. 6 Example of user interacting through air-tap with the AR interface displayed on the HoloLens (AR interface added to the image in post-processing phase).

In 2011 Fite-Georgel [20] specified IAR as the particular application of AR that supports an industrial process.

In general, IAR can be employed to display valuable information in real-time on the real working area; the use of this technology can potentially lead to the following advantages:

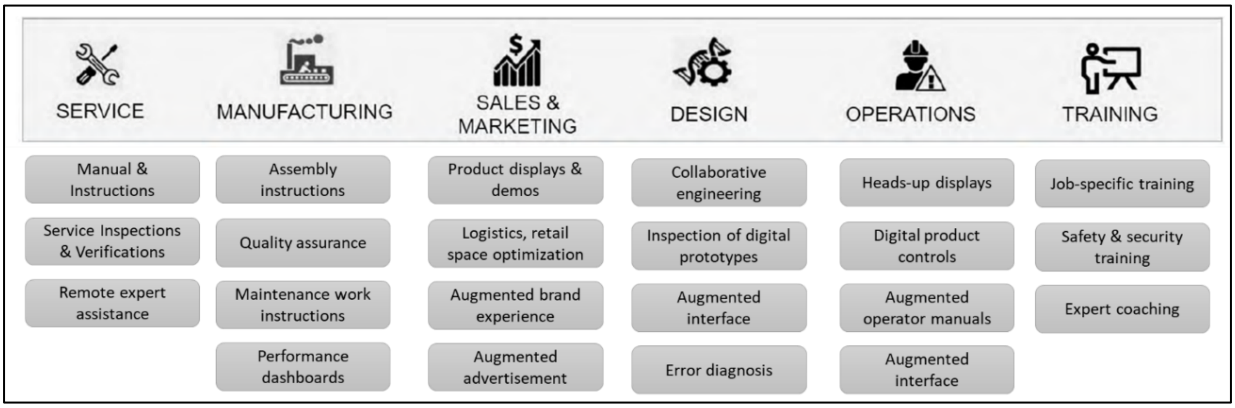
- error rate reduction and the level of detail of information can be adapted to worker's skills;
- employ less-skilled operators: information can be transferred in a more efficient way;
- all the technical documentation is in an electronic format;
- operations can be made in less time, and transfer of experts on-site can be reduced or avoided;
- knowledge is retained in the system and not in people;

1.2. **IAR in the Industry 4.0 Context**

The birth of smart factories, driven by Industry 4.0 (I4.0) paradigm, shifts attention to the novel role of the human operator as a crucial element to deal with new and unpredictable behaviors in smart production systems. Human operator in I4.0 [21] should be extremely flexible and demonstrate adaptive capabilities due to the wide range of problems to solve. Nevertheless, even for flexible operators, it could be difficult to manage the large amount of information that would be available in I4.0 production plants, as well as the rapid changes in the configuration of production lines to satisfy customer requirements.

One of the functions in an industrial plant that will much benefit from I4.0 is that of equipment maintenance. Commercial solutions (e.g., PTC ThingWorx, REFLEKT ONE, Scope AR) for the development of AR maintenance applications are constantly increasing, as well as prototypes. However, research works are still needed to address specific issues, as information comprehension authoring cognitive aspects, and so on. Other issues derive from the operating context. One of these is the difficulty for the operator to remember the location of all equipment in the plant and other useful data. This aspect is due to the rapid changing in plant layouts and the greater amount of data to manage in the context of Industry 4.0.

IAR aims to provide a tool to support operators in the information retrieval about equipment in industrial plants, allowing access even more data. This tool will improve maintenance tasks to reduce the retrieval time of useful information in the maintenance procedure and, consequently, the downtime of the process. Shortly, when structured and unstructured data will become increasingly available from all points of the process (see Fig. 7), the target will move to predictive maintenance, based on fault prognosis.



SERVICE	MANUFACTURING	SALES & MARKETING	DESIGN	OPERATIONS	TRAINING
Manual & Instructions	Assembly instructions	Product displays & demos	Collaborative engineering	Heads-up displays	Job-specific training
Service Inspections & Verifications	Quality assurance	Logistics, retail space optimization	Inspection of digital prototypes	Digital product controls	Safety & security training
Remote expert assistance	Maintenance work instructions	Augmented brand experience	Augmented interface	Augmented operator manuals	Expert coaching
	Performance dashboards	Augmented advertisement	Error diagnosis	Augmented interface	

Fig. 7 IAR value in different points of industrial process.

Taking a snapshot of industrial plants, we can say that most of them are far from being ready for predictive maintenance, although lots of prototypes and theories were presented in the literature. There is still old equipment, and sometimes it is difficult to integrate them with sensors. A pure data-driven approach is far to be implemented, i.e., extracting the process information for maintenance from the records available in process databases and deriving from machine sensors.

Furthermore, employees are accustomed to relying more on their know-how than on new technologies. A knowledge-based approach is still predominant, i.e., exploiting pre-existing knowledge or information about the process connections.

In this context, the introduction of I4.0 features in existing plants will be gradual. A strategy to integrate data-driven and knowledge-based approaches would be needed. The use of AR allows showing equipment information in the form of digital contents, thus augmenting technical drawings.

1.1. An industrial application scenario – the Mill 4.0

In order to introduce the concept of Mill 4.0, we need to make a brief introduction to the milling process.

Fig. 8 A milling plant in the south of Italy.

The milling industry is based on the principle of separating as much as possible the endosperm from the other parts of the caryopsis. Therefore, it can be defined as an industry of extraction and purification. Wheat milling provides, besides flour suitable for the production of bread, pasta, and other products to be used for human consumption. The bran, together with middlings and meal, is currently used for the preparation of animal feed.

A mill can be distinguished into four sections:

1. Grain picking, pre-cleaning and storage;
2. First and second cleaning and conditioning;
3. Actual milling;
4. Storage and packaging of the flour.

The milling process is represented by a sequence of physical operations that, through pre-cleaning, storage, cleaning, breaking, screening and regrinding, allows to separate, in the form of flour, the endosperm from the cortical parts of the caryopsis of the wheat.

The production process of a mill begins with the acceptance of the grain that, after inspection and the taking of samples for analysis, the grain is sent to a pre-cleaning treatment through suction and screening.

The grain is placed in storage structures, horizontal warehouses, or vertical silos, which must have particular suitability requirements for conservation. The milling process is preceded by a further cleaning operation and humidification (conditioning) with the addition of an adequate amount of drinking water. This operation eases the separation of the endosperm from the cortical part and allows the maintenance, constant and controlled, of humidity and temperature during the grinding process. The actual grinding is made of two phases: breaking and regrind.

The main purpose of breaking, which is done by using ribbed cylinders, is to open the caryopsis, detach the endosperm from the cortical part as much as possible and leave the cortical part as wide and flat flakes from which, in a second time, are further separated the fragments of endosperm still adhering. The regrind instead has the function of reducing the flaky particles from the breaks (granites) in flour through the passage on smooth cylinders and subsequent sieving (sifting).

Grain processing takes place in buildings of 6-7 floors (see Fig. 8), where the product is lifted by mechanical or pneumatic means of transport and processed as it falls through the machines. Inside, hundreds of sensors monitor the status of the processing.

Applying the concepts of Industry 4.0 to grain processing plants (Mill 4.0) means creating a fully integrated facility in which the plant communicates in real-time with business management systems.

The trend in the milling industry is to improve efficiency through automation in order to increase worker safety (by reducing access to silos), increase production without affecting product quality, and optimize raw material and finished product inventories. Automating a milling plant means managing in an automatic way the four main phases of the production process described above through the use of sensors, PLC, and SCADA systems.

The integration required by Industry 4.0 means performing intelligent automation by allowing the four sections to communicate with each other in a deterministic manner and provide real-time data to higher levels of the company. All this means implementing a Cyber-physical manufacturing system.

The consequent deep knowledge of the entire process of working the grain from the reception of the raw material to the bagging of the finished product leads to the realization of:

1. A greater optimization in the inventory to obtain efficient management of stocks and of the phases of unloading and loading of trucks, as well as a more precise organization of production and orders.

2. Scheduled maintenance in order to reduce downtime in production cycles.

3. Greater efficiency of the cleaning, grinding and bagging phases in order to increase the production and quality of the final product.

Deep knowledge of the production process is possible only through the acquisition of a large amount of data thanks to measuring points distributed throughout the plant. Current technology has been directed towards the creation of intelligent sensors/devices that allow monitoring all phases of grain processing. Often these are multi-sensor systems that allow the acquisition of quantities of different types in a more compact and intelligent manner. Wireless sensor networks (WSNs) are becoming radically popular in the grain industry.

We believe that AR technology can help the operator inside a 4.0 milling plant to manage this large amount of information provided by the sensorized machines (See Fig. 9) within the milling plant.

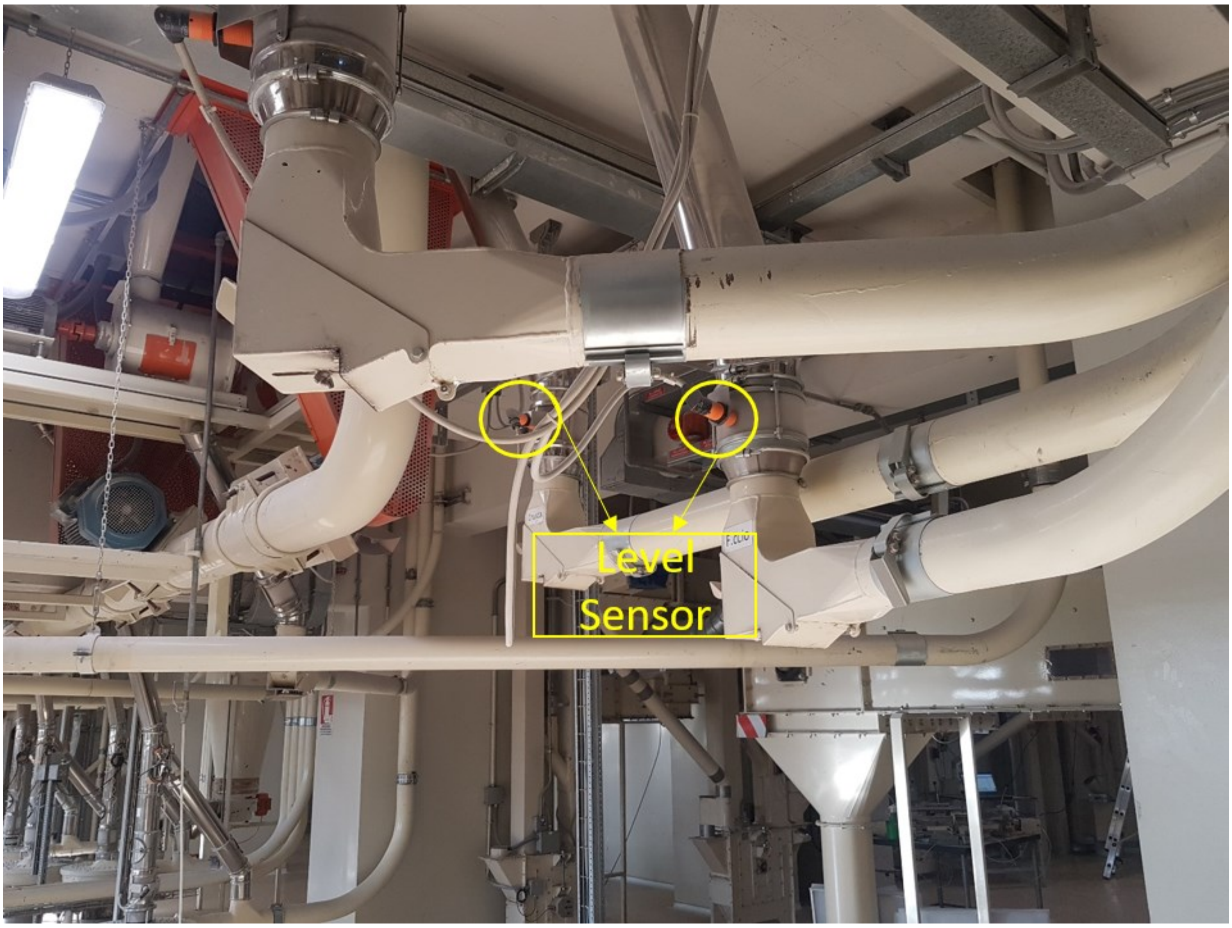


Fig. 9 Section of a grain milling plant with sensor systems, two level sensors are circled in yellow.

To do this, we need to understand what the right choices of AR interfaces are and how to convey the information to the operator in the best possible way.

In the next chapter, we will begin to bring order in the world of AR interfaces, to understand what the trends are in the IAR literature and suggest guidelines for future IAR interface designers.

Chapter 2. State of the art analysis of IAR interfaces

This chapter [1] originated from the idea of bringing order to the many techniques for convey technical information in AR. In fact, as argued by Rolim et al. [22], there is no agreement in the literature about the best way to present information and provide instructions for users via AR. Providing such design guidelines is challenging, because AR necessarily deals with open-ended real environments and each scenario may introduce new constraints. Existing standards such as the Augmented Reality Markup Language (ARML) [23] and the Keyhole Augmented Reality Markup Language (KARML) [24] while generalist, can be used as starting point for future implementations (e.g., to specify nomenclature). The IEEE Standards Associations is developing a family of standards for virtual and augmented reality that addresses aspects such as safety, how different technologies should be defined, and how virtual and real objects should work together.

Therefore, literature is scattered among several proposals of IAR interfaces. We found works using different visual assets based on specific studies [25], [26], [27]. Besides these, for many IAR applications described in the literature, but there are limited details or descriptions of the interfaces, nor motivations for the choices of visualization methods. We also found papers providing design recommendations [28], even for industrial AR interfaces [29]. However, these recommendations need to be integrated with specific insights on the interface, also considering different devices. In fact, the design of IAR interfaces may be further complicated by the nature of AR devices. For example, occlusive visual assets may limit the situation awareness and operator safety when viewed through head-worn displays as compared to those same visual assets presented via handheld IAR devices [30]. Then, a preliminary work to reach guidelines for authors of next-generation IAR technical documentation is that of reviewing how technical instructions were presented in the literature. To the best of our knowledge, there is a lack of literature that systematically studies technical visual assets that can be used in AR user interfaces for maintenance, assembly, and training procedures. Thus, in this work, we want to address

---

[1] The results of the studies described in this chapter were published in the following paper:
Gattullo, M., Evangelista, A., Uva, A. E., Fiorentino & Gabbard, J. L. (2020). What, How, and Why are Visual Assets used in Industrial Augmented Reality? A Systematic Review and Classification in Maintenance, Assembly, and Training (from 1997 to 2019). IEEE Transactions on Visualization and Computer Graphics, 1–1.

the following research questions: "what are the most commonly used visual assets and how are they used in IAR interfaces for maintenance, assembly, and personnel training tasks?”

In this work, we present results from our Systematic Literature Review (SLR) of visualization methods for technical instructions in industrial augmented reality prototypes and concepts for maintenance, assembly, and training procedures presented in the last decade. Based on this review, we further propose a classification of technical visualization methods, considering different aspects in their authoring in IAR interfaces, and defined as follows:

- What is displayed as a visual asset;
- How visual assets convey information; and;
- Why a certain visual asset is used.

This classification could serve to promote community discussion and ultimately go towards standardization.

2.1. Related Work

Azuma's works [31], [32] are a reliable starting point for all the following research in AR. They describe medical, manufacturing, visualization, path planning, entertainment and military applications that have been explored since then. It is interesting to note that most of the applications reviewed made use of 3D models. Other more recent surveys of AR technology, applications, and limitations are those made by Van Krevelen and Poelman [33], Carmigniani et al. [34], Billinghurst et al. [35]. Moreover, in 2008, Zhou et al. [36] provided a successful review of ten years of ISMAR; ten years later Kim et al. [37] updated this survey with a revisiting of ISMAR trends from 2008 to 2017.

2.1.1. Reviews on Applications of AR in Industry

Ong et al., [38] provide one of the first inclusive reviews of IAR research and development, including some of the relevant issues that are limiting the successful applications of AR in the manufacturing field. They summarize the requirements that a successful IAR application should ideally have in terms of hardware and software systems, such as an efficient and suitable user interface that can be conveniently used to interact with the augmented manufacturing environment.

Nee at al., [39] presented some of the IAR applications that are relevant for the manufacturing filed. This work emphasizes the importance of the design phase of an AR application, such as the development of highly interactive and user-friendly interfaces and providing valuable insight in order to make AR an interesting tool in the manufacturing and engineering field.

Syberfeldt et al., [40] focused on the industrial domain, aiming to take the manufacturing industry one step closer to the broad adoption of AR smart glasses. They present a step-by-step process for evaluating AR smart glasses, including concrete guidelines as to what parameters to consider and their recommended minimum values. They suggested an evaluation process for manufacturing companies to quickly make optimal decisions about what products to implement on their shop floors.

Rankohi and Waugh [41] present a statistical review of AR technology in the architecture, engineering, and construction (AEC) industry. They synthesize the current state-of-the-art and trends of augmented reality technologies for construction projects and identify key application areas that could significantly affect the AEC. It is interesting to note that most of the articles reviewed discuss non-immersive user experiences, i.e., desktop-based AR, rather than immersive ones. As seen in other reviews, their work reveals that most of the AR systems found in the literature are prototypes, one-offs, and demonstrations.

Dini and Dalle Mura [42] provide a comprehensive survey that reviews some recent applications in Through-life Engineering Services (TES), emphasizing potential advantages, limits and drawbacks, as well as open issues which could represent new challenges for the future. The main open issues found are usability and portability of AR hardware, small field of view of devices, the visual quality of overlaid images, system delays, and difficulties in the preparation, preparation, programming and setting up of these systems.

Fraga-Lamas et al., [43] describe the basics of IAR and then carried out a thorough analysis of the latest IAR systems for industrial and shipbuilding applications. Different IAR shipyard use cases are described and a thorough review of the main IAR hardware and software solutions are presented. After such a review, it can be concluded that there are many options for developing IAR interface software, but IAR hardware, although it has progressed a great deal in the last few years, it is still not ready for widespread deployment.

Palmarini et al., [44] performed a Systematic Literature Review to evaluate the current state of the art of AR in maintenance and the most relevant technical limitations. From their study, it is clear that there is high fragmentation among hardware, software and AR solutions which leads to high complexity for selecting and developing AR systems.

Bottani and Vignali [45] in a recent survey, classify the literature on IAR from 2006 to 2017 and identify the main manufacturing areas were IAR is deployed. Moreover, their results show that HHDs and HWDs are the most widely used display devices in IAR. Finally, one of the most important insights of the survey is that the results confirm the fact that AR shows great application potential in many industrial operations and, in particular, in the field of maintenance and assembly.

2.1.2. Reviews on a specific AR topic

Kruijff et al., [46] identified the main perceptual problems that affect the correct perception of augmentations on a range of AR platforms: head-worn displays (HWDs), handheld devices, and projector-camera systems. Rolland et al., [47] reviewed optical architectures for see-through HWDs along with key factors and functions required of a successful see-through HWD. This review was made independent of a specific application domain.

Another field of research seen in the literature is that of user-based experimentation. As argued by Swan and Gabbard [48], there is a need to further develop AR interface and systems from user-centered perspectives. They surveyed and categorized the user-based studies that have been conducted in AR, finding that work is progressing along three complementary lines of effort: those that study low-level tasks, those that examine user task performance within specific AR applications or application domains, and those that examine user interaction and communication between collaborating users. Dey et al., [49] present the broad landscape of user-based AR research, providing a high-level view of how that landscape has changed. They identify primary application areas for user research in AR, describe the methodologies and environments commonly used, and propose future research opportunities for making AR more user-friendly.

2.2. Methodology

This review paper was synthesized from the literature using a systematic literature review process [50]; a process used in other AR reviews such as [49], [44]. Our systematic review process was performed into two phases: paper selection followed by paper analysis.

2.2.1. Paper Selection

The paper selection process consists of 5 steps:

1. planning the search;

2. defining the research question;
3. defining keywords and search criteria;
4. searching the papers; and;
5. definition and application of exclusion criteria.

In the search planning, we used five bibliographic databases: Scopus (www.scopus.com), IEEE Explore Digital Library (www.ieeexplore.ieee.org), ACM Digital Library (www.dl.acm.org), Science Direct (www.sciencedirect.com), and Web of Science (www.webofknowledge.com). The search was carried out in April 2020. To answer our research question, we identified three sets of keywords. The first set refers to the technology. We used both "Augmented Reality and "Mixed Reality" because we found that many authors use this more general term to refer to AR prototypes (e.g., [51], [52]). The second set of keywords intended to limit the search to only the industrial fields of maintenance, assembly, and personnel training for industrial activities. We chose these keywords because, as reported by Dey et al. in a recent review [49], the majority of the work in the "industry" category focused on maintenance and assembly tasks. Further, the use of AR in industrial training for assembly and maintenance activities is increasing as revealed by Werrlich et al. [53] then we added also "personnel training." We did not use just "training" to avoid paper in the education field. The third set of keywords intended to limit the research to papers that either presented a prototype (concept) or a framework where a visualization method to display instructions is discussed. Thus, the search terms used were:

("augmented reality" OR "mixed reality") **AND** ("maintenance" OR "assembly" OR "personnel training") **AND** (“prototype" OR "concept" OR "framework" OR "visualization" OR "instruction").

The search was carried out in the title, abstract, and keywords fields for the databases Scopus, ACM, and Science Direct, in all the metadata for IEEE Explore, and in the Topic for Web of Science. With a first search using only the keywords described above, we gathered 1757 papers overall (see Tab. 1). Half of them came from Scopus database. To refine the search, we decided to include only the scientific articles with the following additional selection criteria, where possible:

- written in the English language,
- published in journals or conferences,
- applied to the engineering or computer science field, and,
- published from 1997 to 2019.

Tab. 1 Outcome of the searching phase

		Documents returned	
Database	**Search fields**	**Before refinement**	**After refinement**
Scopus	Title-Abs-Key	880	689
IEEE Explore	All Metadata	280	265
ACM	Title-Abs-Key	170	164
Science Direct	Title-Abs-Key	90	76
Web of Science	Topic	337	282
	Total:	**1757**	**1476**

We started the observation period in 1997 when Azuma published a survey on Augmented Reality [31], also providing a clear definition of it. We excluded papers published in 2020 that is the same year when the search was carried out. After the refinement, the number of remaining papers was 1476. Since this phase has been carried out for each database separately, this number of documents includes duplicates. Removing all the duplicates, the number of papers reduced to 949.

We considered the relevance of scientific impact of the papers using the citation number. For each paper, we retrieved the total number of citations, reported in the databases, and calculated the Average Citation Count (ACC), as suggested in [19]:

$$\text{ACC}= total\ lifetime\ citations/lifetime\ (years) \qquad (1)$$

We wanted to consider only the set of papers that (based on ACC) appear to have made more than a minimal impact, so we discarded papers with an ACC less than 1.5 resulting in a reduced set of 296 papers.

It is worth noting that up to this point neither the title nor the abstract of any paper had been read. Thus, we next shifted our attention to the contents of the remaining 296 papers, defining 2 sets of exclusion criteria: EC1 and

EC2. For each of the 296 papers, the title and the abstract were read in order to apply the first set of exclusion criteria (EC1):

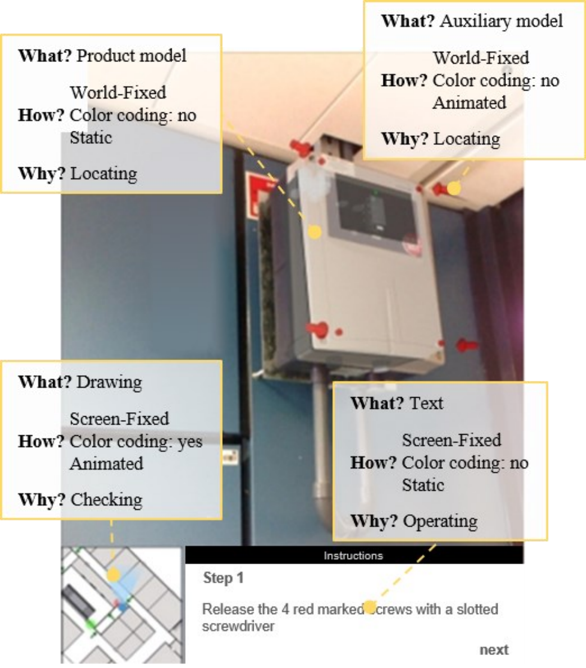
- The paper does not talk about AR or AR is not applied to the industrial domain.
- The paper focuses on industrial augmented reality, but the prototype described is not used for maintenance, assembly, or training tasks.

The result of the application of the EC1 was a list of 171 papers. After this, it was necessary to read the papers in their entirety in order to apply the second set of exclusion criteria (EC2):

- In the paper neither an interface or a prototype is described.
- No useful information is provided in the document to describe the interface.
- The same interface is described in other included papers.
- Applying the exclusion criteria resulted in a final set of 122 papers that we formally reviewed.

2.2.2. Paper Analysis

In the analysis phase, the 122 papers were randomly divided among 3 AR expert researchers and the author of this dissertation in order to carry out independent and parallel reviews. Furthermore, after brainstorming, we reached a common agreement on the data to be collected from each article. This iterative process of meeting and brainstorming among the AR researchers leads to the proposed classification. For each article, we analyzed the AR user interface by disassembling the interface into different atomic elements (see Fig. 10). We considered as augmented elements all the pieces of information used by UI. designers to convey instruction. Thus, we included not only information provided through annotations (i.e., a virtual information that describes in some way, and is registered to, an existing object, as defined by Wither et al. [54]), but also through elements attached to specific positions in the UI. These atomic elements were then added to a classification table created for the systematic collection of data. When analyzing an interface described in a paper, we looked for videos on the web that showed the interface features. When these videos were not available, we sought further insights from within the paper. First, we searched in the figures and their captions. If the information provided in the figures was incomplete, we consulted the body of the paper. In some cases, information about the interface was only present in the body of the paper. During our reading of the papers, we also recorded



Release the 4 red marked screws with a slotted screwdriver

Fig. 10 Example analysis of an according to our proposed classification. We added the yellow boxes, dashed leader lines, and filled circles to illustrate application of our proposed classification.

which type of AR display device was used, distinguishing among head-worn displays, handheld displays, desktop monitors, and spatial AR (SAR) displays.

During paper analysis, we met regularly to discuss papers and UI that were not clear, in order to reach an agreement. From Fig. 12, it is possible to note that the number of reviewed papers is higher in the last ten years of the observation period than in the rest of the period, with a peak in 2018. There were no papers that met our criteria in 1997, 2000, 2002, 2004, 2006 and 2010. In the last five years, after a peak of 11 papers in 2014, the proportion of papers in maintenance field is decreased respect to those in assembly. In fact, there is a strong increase of papers in the assembly field in the last five years (37 papers against 19 in the rest of the period). The papers in the training field were all published in the last decade. Overall, we found most of the papers in the field of assembly (56, or 46%), whereas papers in maintenance contain the highest mean number of visual assets (3.37), as observable in Tab. 2, where summary statistics for all 122 papers are reported.

Papers in the maintenance field have a higher mean number of authors and were published more in journal than to conference venues, contrary to papers on assembly and personnel training (Tab. 2).

In the set of work that we examined, there is a higher proportion of maintenance prototypes tested in real environments, whereas the majority of assembly prototypes were tested in the laboratory. For personnel training, there is almost the same number for each real and laboratory environment (Tab. 2). An explanation could be that maintenance requires a real scenario, whereas an assembly scenario it is easier to reproduce in a laboratory (and sometimes using a simplified form of the actual assembly). In fact, we found several papers using furniture or LEGO assembly applications to describe their research prototype.

Our review suggests that handheld displays are the most commonly used devices for maintenance; HWDs the most common for assembly and training (see Tab. 2). As observable in Fig. 11, handheld displays were used mostly in the last decade with a steady trend. This was expectable due to the availability of commercial smartphones and tablets in these years. HWDs were also used in the first years of observation, but there is a strong increase in the last years with a peak in 2018. This is mainly due to the availability of new more ergonomic HWDs as Microsoft HoloLens and Meta 2. As a consequence, the use of desktop monitors has decreased in the last years. Spatial AR displays were used only in the last decade with a steady trend.

Tab. 2 Summary of the 122 reviewed papers

Application Area	***Paper***	***Mean ACC***	***Mean Author Count***	***Publication***		***Display****				***Test scenario***		***Mean Visual Asset Count***
				Journal	*Conference*	*HWD*	*HHD*	*MON*	*SAR*	*Real environment*	*Laboratory*	
Maintenance	51	5,2	4,59	27	24	18	25	11	0	24	27	3,35
Assembly	56	5,4	3,90	26	30	31	6	14	7	11	45	2,30
Personnel Training	15	7,1	3,73	7	8	10	2	2	1	7	8	3,27
Overall	**122**	**4,2**	**5,53**	**60**	**62**	**59**	**33**	**27**	**8**	**42**	**80**	**2,86**

**HWD = Head Worn Display, HHD = Hand-Held Display, MON = Desktop Monitor, SAR = Spatial Augmented Reality*

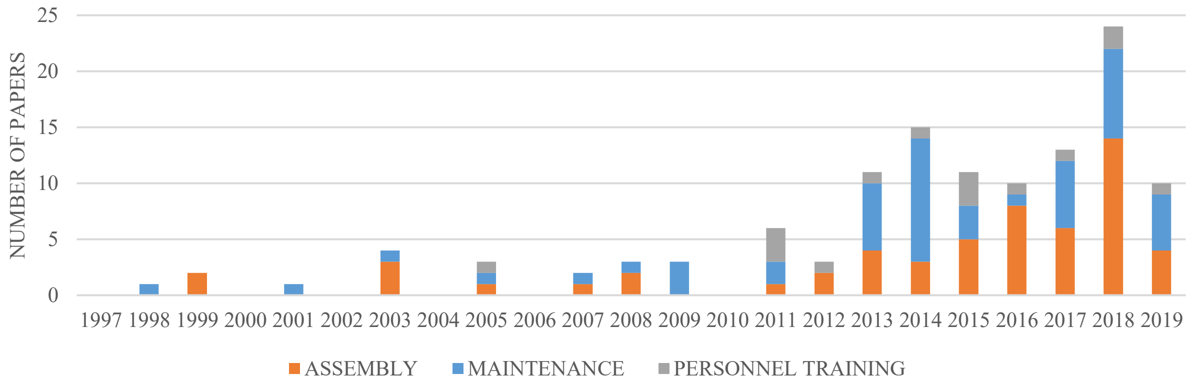


Fig. 11 The number of papers in our review per year where an IAR prototype is presented. 103 out of the 122 analyzed papers are in the last decade (2010-2019) when also "personnel training" topic is more addressed.

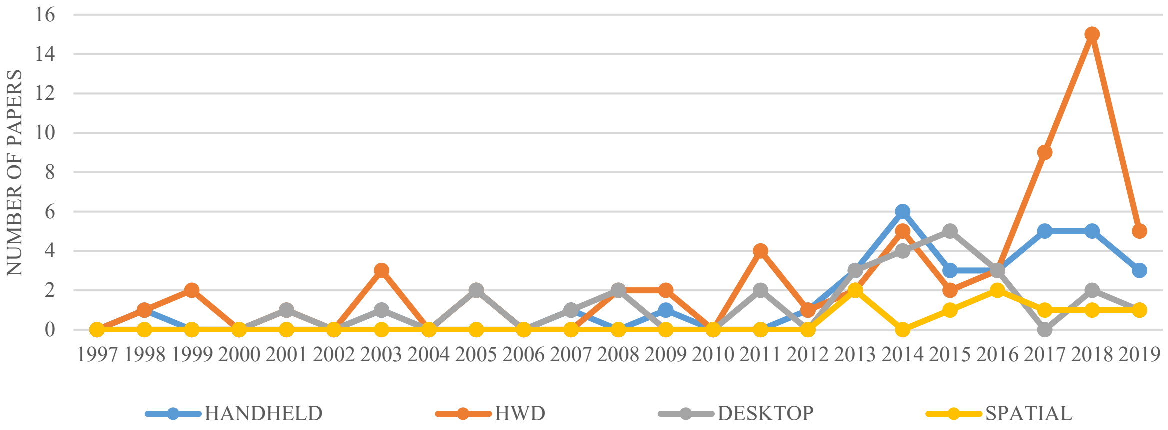


Fig. 12 Trend about the use of AR devices in the prototypes described in the analyzed papers.

2.3. Visual Asset Classification

Based on a preliminary analysis of the papers, we propose a classification for IAR UI visual assets (Fig. 13). To create the classification, we followed the process recommended in [55] to first create an intentional classification that contained mutually exclusive and jointly exhaustive classes and extensions. We then applied a subsequent classing phase where visual assets were assigned to classes. Specifically, we first analyzed which visual assets are used in the literature, i.e., what visual assets are commonly used. We made the proposed classification following the authoring pipeline of an AR scene. We can divide it into two main stages: i) authoring of the single visual assets, that changes according to the type: 3D modeling in CAD software, photograph acquisition, and so on; ii) creation of the AR scene, usually done with development platforms (e.g., Unity 3D or Unreal) where the visual assets are combined with the real scene and additional properties can be added to them.

Then, we made the first distinction, putting into different bins visual assets that needed different approaches in the authoring phase ("what"). This is the reason why, for example, we distinguished between photograph and video: even if both are created using a camera, a photograph is used as it is in the interface, whereas a video often needs postprocessing and then authoring is harder.

Then, we analyzed properties of the visual assets that can be added during the creation of the AR scene and that could give additional information ("how"), as the location in the AR scene, a specific color, an animation. These properties of a visual, i.e., how visual assets are presented, represent the second level of our classification.

Finally, we wanted to study the relationship between the type of visual asset used in an IAR interface and the information conveyed, i.e., why are visual assets used in IAR interfaces.

To enforce mutually exclusive classes assignment, we counted the same types of visual assets (what) if they had different properties (how) or used for different scopes (why). For this reason, in a given paper we could have more than one text, auxiliary model, and so on. Whereas, if a type of visual asset with the same properties and scopes was used more than once in a paper (e.g., for disassembling and re-assembling a product), we counted it only one time. If an instruction was composed of more than one visual asset, we analyzed the two visual assets separately. In the following sections, we describe the classes contained in the proposed visual asset classification.

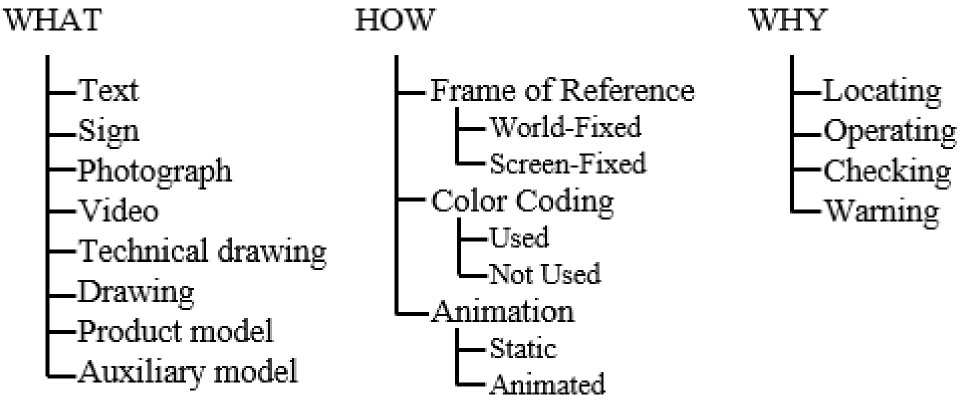


Fig. 13 Our proposed classification of visual assets commonly used in IAR user interfaces as presented it literature 2006-2015.

2.3.1. Class: What (is the visual asset)?

TEXT ► Text is the traditional way to convey verbal information. Authoring text is very simple since it requires just the definition of text content. We include in this category both 2D text and 3D text, as well as text both displayed within bounding boxes and without. Examples of analyzed papers using text as visual asset are [56] and [57].

PHOTOGRAPH ► In this class, we consider assets, whose content is generated through photographs of the real world as acquired by a camera. The use of photographs is very common in manuals, especially digital manuals and instructional websites such as iFixit.com [58]. Examples of analyzed papers using photograph as visual asset are [59] and [60].

VIDEO ► In this class, we consider assets whose content is generated through video recordings of the real world as acquired by a video camera or webcam. Examples of analyzed papers using video as visual asset are [61] and [62].

SIGN ► We applied the definition of Peirce [63] whereby: "a sign is a thing which serves to convey knowledge of some other thing, which it is said to stand for or represent." Signs can be of three types: icons, indices, and symbols. Signs are regulated by standards that could be either International Standards, such as ISO 3864 [64] for safety symbols, or internal practices. The information contained in signs is very focused, which is a key characteristic that distinguishes signs from photographs. Examples of analyzed papers using sign as visual asset are [65] and [66].

AUXILIARY MODEL ► We used the definition provided by Wang et al. [67] that states: "auxiliary models are virtual models for auxiliary instructions". Then, in the proposed classification, auxiliary models are 2D and 3D annotations, used by technical authors for delivering hints to the operator (e.g., guiding operator's visual attention to a detail). Some examples include arrows, circles, and abstract sketches. We did not make a distinction between 2D and 3D elements since the same information can be conveyed by both the 2D and 3D version of auxiliary models. Examples of analyzed papers using auxiliary model as visual asset are [68] and [69].

DRAWING ► In this class we consider all digitized 2D drawings that do not follow formal standards. Examples from the literature include freehand sketches, maps and charts. We also included in this group annotated photographs (i.e., a combination of a photograph and 2D auxiliary models and/or text) since, for the authoring, they require postprocessing of the photograph acquired from a camera (e.g., adding annotations). Examples of analyzed papers using drawing as visual asset are [27] and [70].

TECHNICAL DRAWING ► For technical drawings, authoring is harder because the drawings must follow international standards to deliver constructive and functional information about products (ISO 128-1:2003 [71]). In this category, we include 2D representations in the form of technical drawings displayed as a static image on a canvas, but also 3D graphical annotations, according to ASME Y14.41 – 2003 [72]. Examples of analyzed papers using technical drawing as visual asset are [73] and [74].

PRODUCT MODEL ► We again use the definition provided by Wang et al. [67] that states: "product models are 3D virtual models of product and parts". Product models are the digital representation of real objects (e.g., machinery parts, components, tools) and their authoring is typically made using 3D CAD and 3D modeling tools (e.g., Solidworks, CATIA, Blender). Examples of analyzed papers using product model as visual asset are [75] and [76].

2.3.2. Class: How (are visual asset presented)?

FRAME OF REFERENCE ► The frame of reference for visual assets within an AR interface is an important classification criterion because it can influence the information provided. We used the definition provided by Gabbard et al. [77] initially presented within the context of automotive AR interfaces. They conceptualized the frame of reference from the user's point of view as follows:

- Screen-fixed AR graphics are rendered at a fixed location on the display and are generally not spatially anchored to any specific objects in the scene; and;
- World-fixed (or conformal) AR graphics are rendered such that they are perceived to exist at specific locations in the real world.
- A world-fixed visual asset (i.e., an annotation [54]) often conveys a greater amount of information than the same visual asset presented in a screen-fixed fashion, because the former increases the spatial proximity between the information provided and its real-world referent.

COLOR CODING ► In the industrial domain, the use of color is regulated by international standards and internal practices. For example, colors are used for the identification of material properties in pipes (ASME A13.1, 2007 [78]), for safety symbols (ISO 3864 [64]), and to identify product status in aerospace facilities. The 5S, a common workplace organization method, suggests the use of color in the workspace to enforce sorting, straightening, systematic cleaning, standardizing and sustaining [79]. Thus, we distinguished visual assets whose color is associated with a specific meaning (i.e., purposeful color semantics) from those whose color is arbitrary (or we perceive to be arbitrary based on the paper's figure and/or associated figure caption and text).

ANIMATION ► We distinguish animated visual assets from static ones since the use of animation can provide further directional or temporal information to the users. We consider animated visual assets to be those that change their position/rotation/scale in the interface over time, while keeping the point of view of the real world fixed. Examples of animated visual assets include: a product model of a screw that is animated to show unscrewing (change of position and rotation), virtual arrows that pulse (change of scale), and sliding text (change of position). Videos that occupy a fixed position in the interface are considered static even if the content changes over time.

2.3.3. Class: Why (is the visual asset being used)?

LOCATING ► We consider locating an important use of visual assets, since IAR elements can assist in identifying objects of interest within the scene. In IAR, users need to identify and locate parts both inside and outside their field of view (FOV). Locating is always a supporting task because it does not involve a change in the system status (no action); instead, it is a prerequisite for some task action. A location task could be for instance: locate the screw to be unscrewed, locate the button to be pressed, or locate the tools to be used.

OPERATING ► Operating tasks refer to all actions that are carried out by the user, with and without the aid of tools, that change the state of the scene/system. The operating task is generally performed after a locating task for the target. Representative examples could include unscrew the screw counterclockwise, press a button or raise a lever.

CHECKING ► Checking tasks involve the examination of an object in order to make a decision (e.g., determine its condition, or to detect the presence of something wrong) but without performing the subsequent operation. Checking the oil level, discrepancy checks, checking the pressure on a pressure gauge or checking that a surface is clean are all examples of checking tasks.

WARNING ► In an industrial environment, safety is a priority. Therefore, even IAR interfaces must provide special warnings that indicate a potential hazard or condition that requires special attention, in order to prevent injury or avoid hazards that could threaten operator health and safety. Industrial hazards can be found in almost every work environment (e.g., radiation hazard, overhead hazard, machine safety) and each hazard requires a specific visual asset to reduce ambiguity.

2.4. Results

From our analysis, the 122 papers present 348 visual assets. Looking at the source for the collection of assets, 54 (16%) of visual assets were from videos, 85 (24%) from figures, 156 (45%) from both figures and the body of the paper, while 47 (15%) visual assets were identified using only information presented in the body of the paper.

Tab. 3 gives summary statistics for all identified visual assets. We distinguished among papers in the fields of maintenance, assembly and personnel training.

Tab. 3 Summary of the 348 Visual Asset found in IAR literature.

Application Area	***Visual Asset Count***	***WHAT***								***Information about VA extracted from***			
		Text	*Sign*	*Photograph*	*Video*	*Tech Drawing*	*Drawing*	*Product Model*	*Auxiliary Model*	*Video*	*Figure*	*Figure and body*	*Body*
Maintenance	170	51	4	5	8	3	12	48	39	39	57	48	26
Assembly	129	26	0	6	1	6	7	49	34	8	17	87	17
Personnel Training	49	14	1	1	2	0	3	12	16	7	11	21	10
Overall	**348**	**91**	**5**	**12**	**11**	**9**	**22**	**109**	**89**	**54**	**85**	**156**	**53**

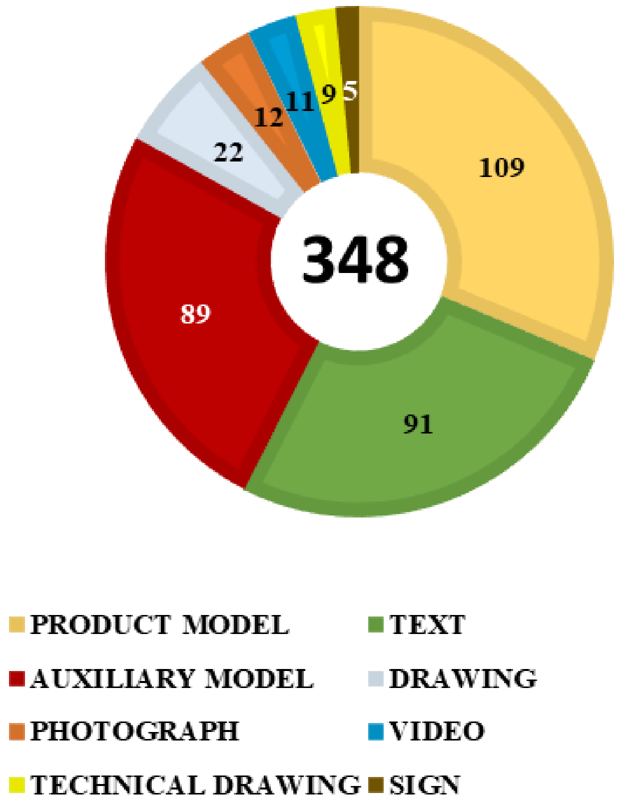


Fig. 14 The number of visual assets occurrences in various application field

The product model is the most common in all application fields (109 occurrences of 348, 31%), followed by text (91, 26%), and auxiliary models (89, 26%), while all the other visual assets were used at lower counts (Fig. 14).

Analyzing the application field (Tab. 3), the number of visual assets in maintenance is much higher (170, or 49%) than in the other two fields (assembly 129 or 37%, personnel training 49 or 14%). For the maintenance field (Fig. 16), the most-used visual asset was text (51 or 30%), for assembly the most-used was the product model (49 or 38%), and for personnel training field, the auxiliary model was most-used (16 or 33%). In assembly, the text was used less (20%) than the other fields (30% in maintenance and 29% in training), while technical drawing was used more (5%).

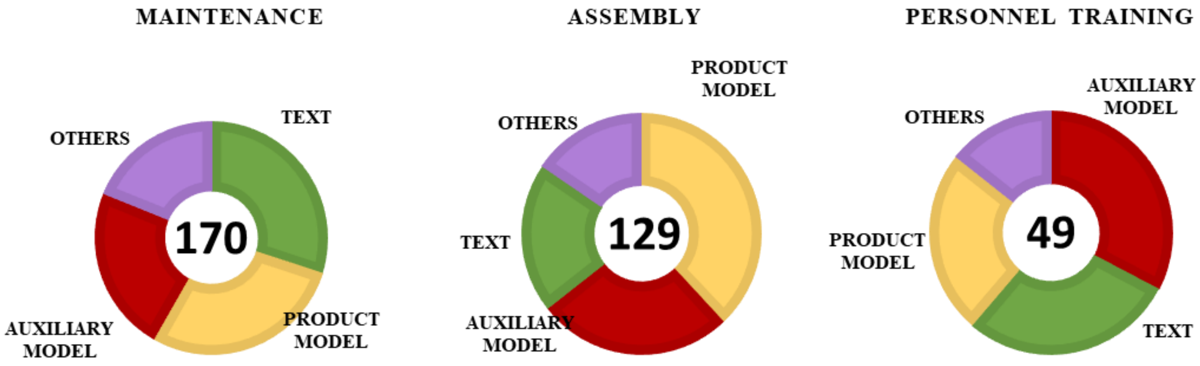


Fig. 15 The most used visual assets change depending on the industrial field.

Fig. 15 depicts results from the "what" and "how" classification. Regarding text, there is no evident preference between screen-fixed (48 or 53%) and world-fixed (43 or 47%). On the

Visual Asset (n°)	Frame of reference	Color coded	Animated
Text (91)	53% 47%	91% 9%	99% 1%
Product model (109)	8% 92%	83% 17%	50% 50%
Auxiliary model (89)	1% 99%	80% 20%	76% 24%
Technical drawing (9)	100% 0%	100% 0%	89% 11%
Sign (5)	40% 60%	80% 20%	100% 0%
Photograph (12)	75% 25%	100% 0%	100% 0%
Drawing (22)	73% 27%	91% 9%	95% 5%
Video (11)	64% 36%	100% 0%	100% 0%

Fig. 16 Results about "what" and "how" classification. CAD models, both product and auxiliary ones, are almost always used as world-fixed and often animated.

contrary, for product model, there is a great predominance of world-fixed assets (100 or 92%) as compared to screen-fixed (9 or 8%). Auxiliary models are almost all world-fixed (88 or 99%).

For signs, there is a slight prevalence of world-fixed assets (3 or 60%). For technical drawing, photograph, drawing, and video there is a prevalence of screen-fixed assets. As regards the color coding, we were surprised to notice that it was rarely meaningful used (only 48 visual assets or 14%). Color coding is sometimes used for text, product and auxiliary model, sign and drawing.

Finally, the animation in visual assets was scarcely used, but when used, were mostly found in product model (54 or 50% in Fig. 15), and auxiliary model (21 or 24%).

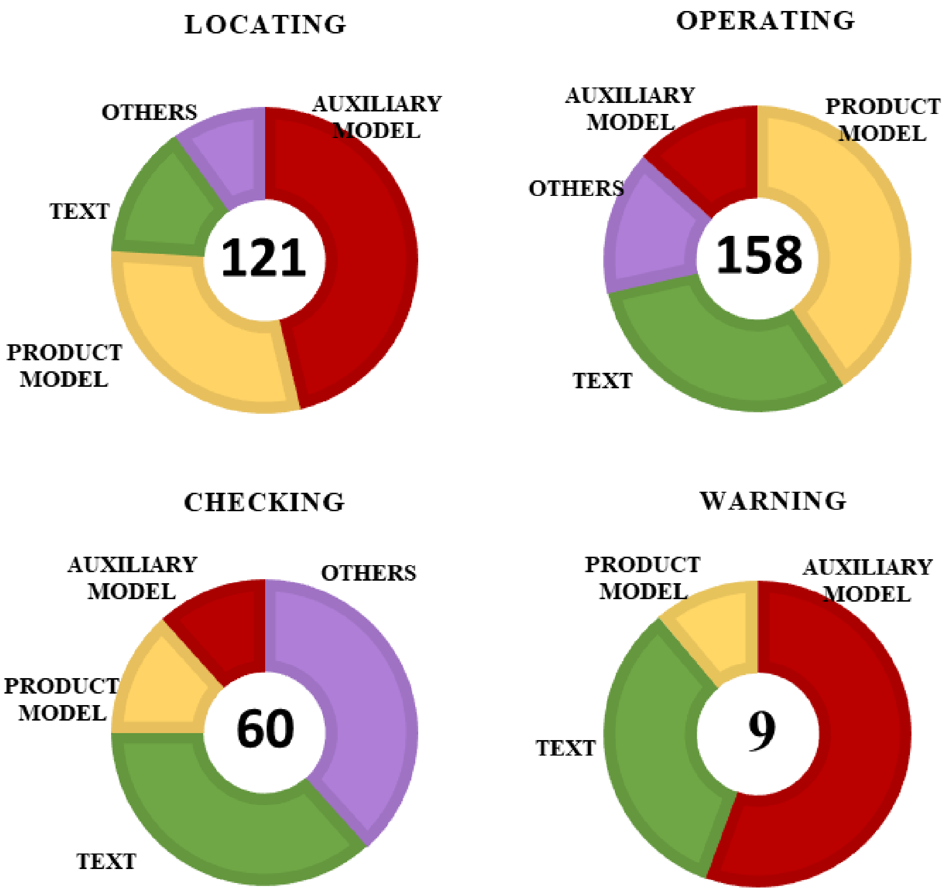


Fig. 17 Results about "what" and "why" classification.

Fig. 17 shows an analysis of why visual assets are used for specific tasks. For locating, the most used was the auxiliary model (56 or 47%), for operating, the product model (64 or 40%), and for checking, the text (22 or 37%). It is worth to note that in checking tasks, the presence of technical drawings is comparable to other tasks (7 or 12%). As to warning tasks, there are very few instances (only nine visual assets), with a prevalence of auxiliary models (5 or 56%).

2.5. Discussion of Results

The proposed visual asset classification and results of our SLR reveal the presence of some interesting patterns useful for answering our research questions: "which are the visual assets and how they are used in IAR interfaces for tasks in maintenance, assembly and personnel training?".

A technical author aiming to design a next-generation manual, exploiting both web and AR content, could start from these results that provide a snapshot of over 20 years of literature on the topic.

A first observation that we can draw from the results, is that locating tasks are often supported through world-fixed, static, either auxiliary or product models (59% overall). The use of CAD models helps operators to identify a real object either observing their virtual copy (product model) or highlighting the space region where it is located (auxiliary model). Thus, it is evident why CAD models are often world-fixed, but perhaps should not be animated since there is limited added value and an unjustifiably high authoring effort. The locating task is accomplished through the perception of visual assets, involving stimulus preprocessing, feature extraction, and stimulus identification. Among the methods for directing visual attention to specific spatial locations, Stork and Schubö [80] distinguished between exogenous (or peripheral) cueing (i.e., presenting salient spatial cues at the relevant position), and endogenous (or central) cueing (i.e., using symbolic cues in order to indicate the spatial position). Peripheral cues afford faster attentional shifts than central cues because the latter need additional time for the interpretation of the symbol. World-fixed assets can be considered peripheral cues since information is presented exactly on the part to be located. This is one of the greatest advantages of using AR as compared to static textbook manuals. Nevertheless, designers should evaluate if the use of a product model would provide more information than an auxiliary model, considering that the formers require a higher authoring effort, cannot be used with SAR, and require precise alignment with real products. Auxiliary models with salient attributes like animation, size, orientation, color and transient luminance changes can provide the needed information for locating single objects in an assembly or object details (e.g., a hole), as in [81]. To locate a group of objects in a large assembly instead, the use of auxiliary models can lead to ambiguous interpretations. In these cases, the use of a product model is justified to highlight the exact group of objects involved, as in [82], [83], and [74].

A second observation is that operating tasks were achieved mainly using world-fixed, animated product models (27%). This is an expected result because the main information conveyed in an operating task is the way to operate on objects (e.g., the way to assemble two parts), and the use of animations of product models provides a powerful preview of steps of the task to accomplish. Operators watch the animation and then just have to replicate what they watched. The same result could be achieved through a video tutorial, but CAD models have the benefit of being registered to their real components to be handled. World-fixed product models are indeed peripheral cues whereas videos are central cues, thus in the former there is minimal demand to shift attention between the information and the object to handle. Nevertheless, operating tasks highly depend on task difficulty. Then, for low difficulty task, product models could provide too details that are not needed. For example, to instruct an unscrewing operating task, it is not necessary to have the animation of a virtual screwdriver and screw. Other visual assets can be explored in these cases such as auxiliary models and signs that require less authoring effort and provide operating task information without too many extraneous details.

As to checking tasks, there is a higher scattering among visual assets, with a predominant preference for text (30%). The range of checking tasks is so wide that the proper visual asset should be chosen case by case. The use of text is justified since it is the simplest method to describe the way the checking task should be carried out, e.g., through a visual inspection. Text is needed to fully describe the context and/or to provide quantitative values of physical properties (e.g., the pressure of a manometer). Thus, in most of the AR interfaces analyzed, authors tended to use the same text information that would be present in a traditional manual. Then, specific research could be done for checking tasks exploring the use of other visual assets, as static product models for discrepancy checks, as done in [84]. Furthermore, studies on text optimization in AR interfaces are of utmost importance, especially as regards visualization style, translation issues, summarization techniques.

Considering the overall results of this review, we found that the most used visual assets are product models, followed by text, and then auxiliary models. All the other visual assets are less common. Thus, there is still a high burden of authoring, caused by the use of product models, which can be the cause of the limitation in the scalability of the AR prototype applications. Furthermore, ongoing research is showing that effectiveness of product models in IAR is still to be proved, as argued by Radkowski et al., who claim that "a user needs more time to understand complex 3D models, which is one reason why their usage is not recommended to display instructions [27]." A possible explanation for the scarce use of some 2D visual assets such as photograph, video, drawing, technical drawing and sign could be that many of the interfaces have been designed with the scope of demonstrating the effectiveness of novel tracking systems, as well as novel techniques for rendering virtual content in three dimensions. Therefore, demonstrating the effectiveness of these techniques through 2D contents would not have been possible. Moreover, in other cases, it could be just a design choice, in fact photograph, video, drawing and technical drawing occlude a large portion of the real world, hiding what is behind them, especially when they are used world-fixed. This issue concerns all visual assets that fill a rectangular area of the visual interface. The use of these visual assets, rendered transparently and in a small size, reduces occlusion, but the information comprehension could be compromised. Other visual assets, such as signs, are not widespread probably because they introduce the challenge of defining a standard 2D sign vocabulary to convey technical instruction [65]. However, signs are easier to recognize and comprehend than other complex 2D elements such as photographs, which are elaborated and full of detail, sometimes unnecessary. Moreover, signs cause a minor occlusion of the real scene and they could also be displayed screen-fixed on the interface.

Finally, the association of specific information to the color of a visual asset (color coding) has been rarely used in the analyzed interfaces. The scarce use of color coding may be due to the low consideration of this technique as a means of communicating specific information. Probably, IAR researchers have focused more on aspects such as tracking, visualization and interaction techniques, neglecting aspects that may seem secondary such as convey information with color coding.

To the best of our knowledge, this is the first review about the use of visual assets in IAR interfaces. Thus, our results are hard to compare to other works in the field. In [44], 2D/3D models are used more than text in maintenance. If considering product and auxiliary models together, our results are consistent with [44]. However, they found more animated than static models.

While the results presented herein are a useful starting point for classifying and discussing what, how and why IAR visual assets are used, we cannot directly generalize these findings to all existing AR interfaces in the literature (industrial or otherwise). This is just a snapshot of 122 selected IAR applications. Moreover, the visual assets analyzed herein are not necessarily the choice of an optimal IAR interface design. In fact, there are many factors to be taken into account to define an "optimal" IAR interface such as: cognitive effort (e.g., a 3D model is more complex than plain text [27]), effects of the interface on behavior and situational awareness, authoring [85], occlusion [86], and style [87] to name a few.

We are continuing this research and we started from a heuristic evaluation considering the advantages and disadvantages of the proposed visual assets [88]. From this initial research, it is possible to reveal some future directions for the research in this field. For example, the use of signs together with auxiliary models could be explored as an alternative to the most popular product models for operating instructions. Authoring of both signs and auxiliary models is done first defining a library. Then when a technical writer creates a new instruction document, a predetermined sign and auxiliary model can be easily recalled from this library. In this way, authoring involves less effort since a standard library of visual assets can be reused in many IAR applications. However, currently, there are no standards to follow, thus future research can be focused on the definition of standard libraries of visual assets.

Other future directions can arise from our review. One of these could be a study for a wider exploitation of color coding to convey information, also considering limitations due to color blindness [89]. Specific research on checking tasks is also needed since in the literature this type of instruction has been presented with various visual assets.

Finally, future studies are needed to find what are the optimal ways to provide comprehensive instruction - i.e., a combination of location, operation, control, and warning tasks - by combining different visual resources, and supporting context-aware IAR interfaces that adapt to the difficulty of the task and the knowledge of the operator, as required by the Industry 4.0 paradigm and thus also to the future vision of a 4.0 Mill.

With this view, in the next chapter we will continue with the study of IAR interfaces, a survey with potential IAR designers will be presented.

Chapter 3. Investigating technical writers' preferences on IAR interface design

In the previous chapter, we put in order on the visual assets used in the literature. In this chapter we will approach the same topic from a different point of view. A survey will be carried out with potential technical writers, revealing the preferences they have in the design of IAR interfaces and the visual assets they prefer to use in these interfaces.

Most of the technical writers in a company have little or none experience with designing graphical user interfaces (GUIs) as well as with AR. As already observed by Engelke et al. [26], traditional paper documentation templates (often deployed as PDFs) are an established state of the art in industry and consumer products. Whit respect to traditional technical documentation, mainly based on text and images, AR offers the opportunity to exploit other visual assets [90] (e.g., videos, CAD models). Then, authoring of technical documentation is harder due to the choice of optimal visual assets, which is mainly affected by the information to convey and the AR display used. To the knowledge of the author of this dissertation, there are neither specific standards nor literature studies that guide technical writers in this choice.

On the other side, the literature is scattered among various proposals of AR interfaces for industrial applications. However, in most cases, they are not scalable [91], i.e., they work well only for the specific use case addressed in that research. One reason could be that the GUI design is left to the developers' creativity, usually with a lower level of experience in writing technical documentation than experts in this field, and also without a detailed study of that specific industrial scenario at the shop floor. It is also hard to extract guidelines from these studies, as most of the IAR systems lack exhaustive GUI descriptions, as well as reasons for choosing specific visual assets. As a result, some visual assets are not used optimally, while others are completely neglected.

Hence, the authoring of IAR applications requires knowledge about AR issues, GUI designing, and technical matters (related to assembly/maintenance) at the same time. Therefore, we made a user study with the goal of understanding which are the preferred visual assets by potential IAR technical writers, i.e., people that have knowledge in all the above three fields. At the beginning of the study, we formulated these research questions:

- Which are the visual assets preferred by potential IAR technical writers?
- How are these preferences influenced by information types?
- Can these preferences be generalized for all the categories of AR displays?

In this chapter[2] we answer these research questions. We selected a sample of more than 100 users with certified knowledge in AR, GUIs, and assembly/maintenance procedures, but with different levels of familiarity, and provided them with a questionnaire.

3.1. Materials and Methods

The questionnaire was designed to understand users' preferences about visual assets, in relation to the information to be conveyed and the AR display used. The categories of AR displays considered: Head-Mounted Display (HMD), Handheld Display (HDD) and Spatial Augmented Reality (SAR).

A preliminary analysis of ten assembly/maintenance manuals allowed us to understand that a technical instruction is composed of various information required or obtained at the start and end of an action. For every information to be displayed by AR, it is possible to use a single visual asset. Thus, we classified information into six information types, considering that, for every information type, a single proposal of visual asset can be done. The six information types found are:

- IDENTITY: e.g., the identity of a part to position, of an object to grasp.
- LOCATION: e.g., location and destination of an object.
- ORDER: e.g., order to do a motion or a structured sequence in a plan.
- WAY TO: e.g., the way to dis/assemble parts, to use an object.
- NOTIFICATION: e.g., confirmation that parts are dis/assembled or information that a problem is occurring/has been solved.
- ORIENTATION: e.g., the initial or desired orientation of an object.

From the literature, it is possible to extract a list of visual assets that can be used in industrial AR applications [90]:

- TXT: text.

---

[2] The results of the studies described in this chapter were published in the following paper: Gattullo, M., Dammacco, L., Ruospo, F., Evangelista, A., Fiorentino, M., Schmitt, J., Uva, A. E., (2017). Design preferences on Industrial Augmented Reality: a survey with potential technical writers. (2020). 2020 IEEE International Symposium on Mixed and Augmented Reality, 172-177.

- SIG: signs i.e., “a thing which serves to convey knowledge of some other thing, which it is said to stand for or represent” [92].
- PHO: photographs of the real-world as acquired by a camera.
- VID: video recordings of the real-world as acquired by a video camera.
- DRA: drawings, e.g., freehand sketches, maps, charts, or other digitized 2D drawings that do not follow the normal standards.
- TEC: technical drawings that follow international standards to deliver constructive and functional information about products.
- PDM: product models, i.e., 3D CAD models of product or parts (e.g., machinery parts, components, tools)
- AUX: auxiliary models, i.e., 2D or 3D graphic elements for auxiliary instructions (e.g., arrows, circles).

To gather preferences in the questionnaire, we displayed how the information will appear with the eight visual assets in a screen-based AR application. We showed all the visual assets for the six information types, extracting them from the assembly instructions of “Model Pick-up truck” (Fig. 18). The entire production cycle of the pick-up truck is carried out in the in the “c-factory,” a laboratory of the FHWS University (Germany), where it is possible to simulate in miniature an entire production cycle in a smart factory. The assembly steps at the pick-up are nine and we chose the steps 8 and 9 (8: Removing screws from the magazine, 8.1: Removing a screwdriver from the holder, 8.2: Placement of the screw, and 9: Removal of the finished component) because they involve all the six information types:

- IDENTITY: “Identify the screw”
- LOCATION: “Destination of the screw”
- ORDER: “Structured sequence defining how screws are going to insert”
- WAY TO: “The way to assembly the screws”
- NOTIFICATION: “Confirmation that the parts are assembled”
- ORIENTATION: “Desired orientation of the pick-up”

Fig. 18 The "Model Pick-up truck" used as case study. We derived visual assets for instructions in step 8 and 9 that contained all the six information types.

The questionnaire consists of three sections. In the first section ("familiarity"), the participants are asked about personal information and user familiarity with Augmented Reality, Graphic Interface design, Assembly/Maintenance procedures and frequency of use of AR displays (HMD, HDD, SAR). A 5-point Likert scale was used for both familiarity (1, Not at all familiar – 5, Extremely familiar) and frequency of use (1, Never use - 5, Frequently use). In Tab. 4 there is the subdivision of the participants about their familiarity level, while in Tab. 5 about their frequency of use of AR displays.

Tab. 4 Level of familiarity of selected users with: AR, GUI and Assembly/maintenance

	AR	GUI design	Assembly/ maintenance
Not at all familiar	5	10	4
Slightly familiar	18	34	21
Somewhat familiar	33	23	24
Not at all familiar	30	31	29
Slightly familiar	19	7	27

In the second section ("information type"), the users were asked to provide a rating, using 5-point Likert scale (1, bad – 5, good), for every visual asset, independent of the AR display. To help users in the decision, they could watch a video that showed a preview of how every visual asset would appear in a monitor-based AR application. In some cases, it was not possible to convey certain information types through some visual assets (e.g., auxiliary model for identity). The displaying of the video and the rating was repeated for the named six information types.

Tab. 5 Frequency of use of selected user with: HWD, HDD, SAR

	HWD	HDD	SAR
Never use	17	2	44
Almost never	48	1	39
Occasionally/Sometimes	26	16	15
Almost every time	6	20	5
Frequently use	8	66	2

Finally, in the third section ("AR display"), users were asked to provide a ranking of the visual assets for the three AR display technologies (HMD, HDD, SAR), based on their previous experiences. Our initial aim was to evaluate this effect in the c-factory laboratory, showing the visual assets on the three AR displays, but it was not possible due to COVID-19 related restrictions. The questionnaire was carried out by 105 voluntary people, whom 2 managers, 10 employees, 3 faculty, 21 PhD or researchers, 69 university students, of which 41 enrolled at University of Applied Sciences Würzburg-Schweinfurt - Germany, 26 enrolled at Polytechnic University of Bari - Italy and 2 enrolled at other universities. We selected users to provide the questionnaire among all those, who have a background in engineering and have knowledge about GUIs and AR. The gender division is: 1 diverse, 22 females, 82 males. The average age of the users is 28.47 years (min 20, max 62, SD 7,81). The questionnaire was created with the tool www.surveyanyplace.com and was sent to the selected users that could compile it by their own. Filling in the questionnaire took approximately 10 minutes.

3.2. **Results**

The responses of all the people that completed the questionnaire were collected. Then, those of users that stated to be “not at all familiar” with either AR or GUIs or assembly/maintenance procedures were discarded. Therefore, the data analyzed derived from 94 users. Since data are ordinal (i.e., ratings from 1 to 5 for the “information type” section and rankings from 1 to 8 for “AR display” section), statistical analysis is done by the Kruskal Wallis test. The results of the second and third part of the survey have been analyzed separately: information type and AR display. For the “AR display” section, data from users that stated to have never used the display for which we were performing the analysis were also discarded. Thus, data analyzed are from 81 users for HWD, 93 for HDD, and 59 for SAR. All the analyses, whose results are reported in Tab. 6, revealed a statistically significant difference among the visual assets for every information type and every display.

Tab. 6 Results of statistical analyses about comparison of visual assets.

Information type	Result of Kruskal Wallis test
Identity	$\chi^2(5) = 91.687$, $p < 0.001$
Location	$\chi^2(6) = 247.167$, $p < 0.001$
Order	$\chi^2(4) = 179.409$, $p < 0.001$
Way to	$\chi^2(7) = 277.719$, $p < 0.001$
Notification	$\chi^2(6) = 142.395$, $p < 0.001$
Orientation	$\chi^2(6) = 253.160$, $p < 0.001$
AR display	**Result of Kruskal Wallis test**
HWD	$\chi^2(7) = 213.647$, $p < 0.001$
HDD	$\chi^2(7) = 190.801$, $p < 0.001$
SAR	$\chi^2(7) = 37.567$, $p < 0.001$

We made pairwise comparisons to reveal the most and least preferred visual assets. We reported the median ratings for every combination of visual asset and information type in Tab. 8 marking with ⁎ the visual assets with the highest rating and with † those with the lowest. If more than one cell is marked with the same symbol in a row, it means that pairwise comparisons did not reveal a statistically significant difference between those visual assets; thus, they are equally preferred. Results revealed that the product model is the most preferred visual asset for every information type, except for “notification” where we were not able to use it. In this case, they suggested sign, drawing, and auxiliary model. However, only for location users had a clear preference for the product model. For all the other information types, also alternative visual assets gather similar preferences as video and auxiliary model (Fig. 19). On the other side, users showed a scarce preference for text as well as for sign, except for notification.

The results of pairwise comparisons for the AR display effect are reported in Tab. 7 We ranked visual assets based on the mean ranks: green cells mean a statistically significant difference between that pair of visual assets. Product model, auxiliary model, and video (in this order) are the most preferred visual assets for HWD. Video and product model are the most preferred visual assets for HDD. For SAR there is a greater uncertainty: there is only a slight preference for auxiliary model.

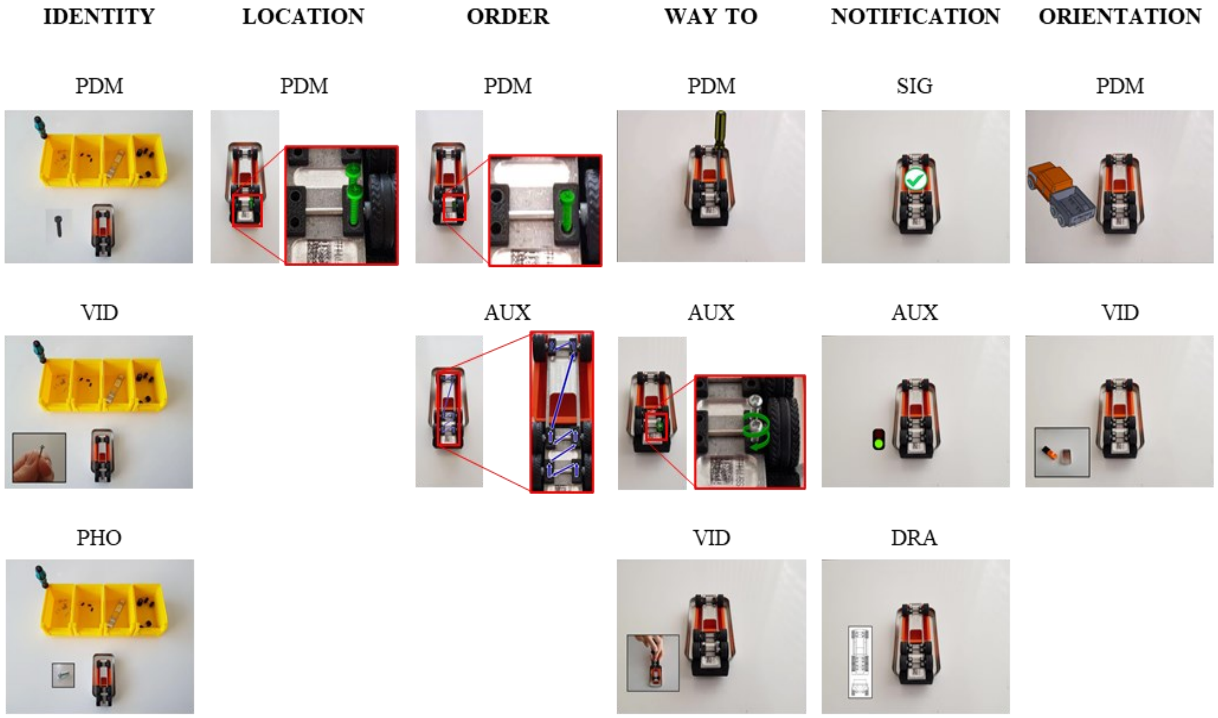


Fig. 19 most preferred visual assets for each information type. The product model is suggested by users for every information type, except that for "notification" where it cannot be used.

Tab. 8 Median ratings for every combination of information type and visual asset.

Information Type	Visual Asset							
	TXT	SIG	PHO	VID	DRA	TEC	PDM	AUX
IDENTITY	$2^{\dagger}$		4^{*}	4^{*}	3	3	4^{*}	
LOCATION	$2^{\dagger}$		3	4	4	4	5^{*}	4
ORDER	$2^{\dagger}$			2	3		5^{*}	4^{*}
WAY TO	$2^{\dagger}$	$2^{\dagger}$	$2^{\dagger}$	4^{*}	3	3	5^{*}	4^{*}
NOTIFICATION	3	4^{*}	$2^{\dagger}$	$2^{\dagger}$	4^{*}	$2^{\dagger}$		4^{*}
ORIENTATION	3	$2^{\dagger}$	3	5^{*}	3		5^{*}	3

Visual assets in cells marked with ⁎ are significantly better than those in other cells in a row; visual asset in cells marked with † are significantly worse than those in other cells in a row; blank cells indicate that it was not possible to find that visual asset for that information type.

Tab. 7 Results about the preferred visual asset for each AR display.

HWD	PDM	AUX	VID	DRA	TXT	TEC	SIG	PHO
PDM		⬜	🟩	🟩	🟩	🟩	🟩	🟩
AUX			⬜	🟩	🟩	🟩	🟩	🟩
VID				🟩	🟩	🟩	🟩	🟩
DRA					⬜	⬜	⬜	⬜
TXT						⬜	⬜	⬜
TEC							⬜	⬜
SIG								⬜
PHO								
HDD	VID	PDM	AUX	PHO	DRA	TEC	TXT	SIG
VID		⬜	🟩	🟩	🟩	🟩	🟩	🟩
PDM			🟩	🟩	🟩	🟩	🟩	🟩
AUX				⬜	⬜	⬜	🟩	🟩
PHO					⬜	⬜	🟩	🟩
DRA						⬜	⬜	🟩
TEC							⬜	⬜
TXT								⬜
SIG								
SAR	AUX	PDM	VID	TXT	PHO	SIG	DRA	TEC
AUX		⬜	⬜	⬜	⬜	🟩	🟩	🟩
PDM			⬜	⬜	⬜	⬜	⬜	🟩
VID				⬜	⬜	⬜	⬜	🟩
TXT					⬜	⬜	⬜	⬜
PHO						⬜	⬜	⬜
SIG							⬜	⬜
DRA								⬜
TEC								

Green cells indicate that there is a statistically significant difference between the visual asset in the row and in the column, otherwise for gray cells.

3.3. Discussion of Result

The results of our user survey unveil the presence of some noteworthy patterns useful for answering our research questions: “Which are the visual assets preferred by potential IAR technical writers?” and “How are these preferences influenced by information types?”

The first remark that we can draw from the results is that product model is the most preferred for all information types except for “notification” (where it cannot be used). This result is not surprising because the use of CAD models in AR is very common in the scientific literature [93]. Product models are mainly used by exploiting the potential of IAR to superimpose virtual objects on real ones, to create the perception of a scene where virtual and real coexist. In particular, in “identity” and “location” information types, the use of product model helps operators to identify a real object either observing their virtual copy or highlighting the space region where it is located, for example with superimposition on a real object in semi-transparency or animated transitions such as blinking. In addition, for “order,” product model can be useful to identify an assembly sequence by showing it through animated 3D models. Similarly, the “way to” information can be conveyed through an animated product model also showing the correct tools to use or providing a preview of the task to be performed by operators. In this way, they watch the animation and replicate what they just watched. Finally, the product model can also be used to convey information about the “orientation” of a part to facilitate the work process.

This result is very promising, it would allow using product model as a default visual asset in IAR applications since technical writers suggest using it for a large amount of information, even of different nature. Nevertheless, other factors must be considered besides the engagement of potential technical writers. In fact, the literature on this topic also revealed some disadvantages to the use of product models in IAR. One of the biggest disadvantages of the product model comes from the authoring effort spent on modeling of 3D parts and assemblies. In fact, authoring of product models requires competence in 3D modeling and the effort spent in authoring is strictly related to the complexity of its geometry, material appearance and animation. Moreover, product models are highly sensitive to the 3D registration accuracy. In fact, a discrepancy between the virtual model and the real object in the assembly scenario can causes visual coherence issues and can lead to low user acceptance. Finally, ongoing research is showing that effectiveness of product models in IAR is still to be proved, as argued by Radkowski et al. [94]. The author claims that “a user needs more time to understand complex 3D models, which is one reason why its use could be not recommended to show complex instructions”. Furthermore, for some information it is not justified the use of a product model. For example, in our case study, for “location” and “order,” the presence of the CAD model of the screw does not add information respect to other simpler representations, i.e., auxiliary models.

The results of the survey in some cases, show that users also indicated alternative preferences to the product model. For the information type “identity”, photos and videos are also recommended. In fact, a photograph or a video of an object helps to mentally associate the object shown in the interface with the one in the real scenario. In our case study, the video of the screw does not add information respect to the photograph, but for more complex components, its use can be justified. As already argued, the information type “order” can be conveyed even with the auxiliary model instead of the product model. In fact, with the use of the arrows, you can indicate a precise task execution order by describing a pattern, using the tip and tail of the arrows appropriately. The information type “way to” presents video and auxiliary model as alternatives to the product model. Videos are familiar to designers of IAR applications because they are widely used in do-it-yourself guides to show how to perform a certain operation. Auxiliary models can be used to convey “way to “information only for simple tasks such as unscrewing or tightening a screw, but it may be difficult to convey information for more complex tasks or when specific tools must be used. The information type “orientation” can be easily provided even with a video, pre-recording with a camera the sequential position that an object must have in the real scenario. Finally, the information type “notification”, according to the users, can be shown through a sign, a drawing or an auxiliary model. They are all visual assets that convey information in a pictorial way. The reason for this preference could be ascribed to everyday life where pictograms are used to convey notifications in computer interfaces or in the traffic signs.

A second noteworthy result, which emerged from the questionnaire, is that users do not consider text convenient for conveying information into the IAR interfaces. On the one hand, this result is somewhat surprising since text is the traditional way to convey verbal information and is plenty used in traditional maintenance/assembly manuals. However, on the other hand, studies have shown that visual instructions are cognitively favorable by people as they are easier to comprehend and remember than text information [95]–[97]. Most of the survey participants were digital natives who grow up immersed in digital media, thus thinking and learning differently from those who grew up with printed text, as revealed by Thompson [98]. Therefore, they prefer graphics to text [99]. This result cannot be neglected in the design of IAR interfaces. Even if text instructions were proposed in several IAR prototypes, some issues would occur. In fact, a very long text instruction could disturb the operator and excessively occlude the real scene. Moreover, even if the authoring of text is very simple, translatability issues must be considered. Thus, research studies are still needed to optimize its usage. For example, as regards legibility as made in [100], [101], while a solution to overcome length and translatability issues could be that of simplifying text through the use of ASD Simplified Technical English, as proposed in [102].

The third research question, i.e., if user preferences could be generalized for all the AR displays, remains open. In fact, more reliable insights will come from planned future tests in laboratory with the real displays, but some considerations can also be extracted from the results of this study. For HWDs and HDDs, potential IAR technical writers suggest using product model and video. This result is not surprising since there are no big drawbacks in the use of these visual assets on these displays. Nevertheless, given that a crucial problem for HWDs and HDDs is the limited field of view, we expected a greater preference for auxiliary models and signs since they cause less occlusion of the real-world respect to other visual assets. This result was observed only for auxiliary models. As to SAR, it is hard to propose a preferred visual asset. This suggests that specific research is needed for this technology that is still not mature. However, the slight preference for auxiliary model is justified since they were effectively used in the literature [103].

The contribution presents the results of a survey with potential IAR technical writers, about the choice of the visual assets in IAR interfaces. Product model revealed to be the most preferred for all information types except for “notification,” where it cannot be used. In this case, users suggested using pictorial visual assets as drawing, signs, and auxiliary model. Alternatives to product model were also proposed: video and photograph for “identity,” auxiliary model for “order”, video and auxiliary model for “way to,” video for “orientation.” Text was the least preferred visual asset.

The main limitation of this work is that the judges provided by users do not come from a direct experience of the visual assets on an IAR interface. They arise from watching a video that showed a preview of how every visual asset would appear in a monitor-based AR application. However, this should not bias the results as regards the influence of the information type, whereas it is a limitation as regards the effect of AR displays. Unfortunately, we could not evaluate this effect in the c-factory laboratory, showing the visual assets on the three AR displays, due to COVID-19 related restrictions. However, we planned to make this evaluation in future studies, where we also want to measure user performance in the real assembly scenario comparing the most preferred visual assets revealed by this study. This chapter concludes the search for guidelines for creating IAR interfaces. This work has outlined well-defined trends that could be used for the creation of IAR interfaces of the future.

In the next chapter we will address the topic of AR technology scouting. The number of both hardware and software solutions within the AR landscape are numerous. Therefore, through a patent analysis we are going to capture what are the trends in terms of enabling technologies, geographical and industrial distribution of companies that patent on AR technology, thus we can choose the hardware and software technologies to implement in our case study.

Chapter 4. Unveiling trends in AR key technologies through a patent analysis

To properly understand the AR technologies that can be implemented in a Mill 4.0, we need to understand the trends in AR enabling technologies. Then, once this is done, we can choose the best technologies to implement our AR system. Indeed, AR is expected to open a wide range of new opportunities in the manufacturing sector.

In the near future, also AR consumer demand is likely to grow. Accordingly, while the global AR market was valued at USD 11.14 billion in 2018, it is expected to reach USD 60.55 billion by 2023, with an annual growth rate of 40.29% during this 5-year forecast [104]. The key success factor for the growth of AR in the consumer market is related to the increased use of smartphones, tablets, and other devices for the implementation of AR [105]. In particular, Head-Mounted Displays (HMDs) are the most promising solutions deemed to boost the growth of the AR market [106]. In fact, major companies such as Microsoft Corporation, Magic Leap Inc., and DAQRI LLC have developed their own HMDs [107]–[110], proving to believe in their market potential. Given the dimension and potential rapid expansion of the AR market, the R&D efforts in improving existing AR solutions and developing new ones are rising, especially considering that AR technologies are far from fulfilling their ultimate potential.

AR is almost fifty years old in industrial research and scientific literature. Still, the development of AR technologies is growing at a very fast pace and is scattered among different businesses, academia, and sciences. Therefore, the study of the AR domain is not an easy task. Moreover, AR integrates different systems/solutions, needs specific applications for each industry, and is developed by different organizations worldwide, further hindering the possibility to keep pace with the evolution of AR. Eventually, it is difficult to unveil how the technological trends of AR have evolved over time, with negative consequences for planning the directions for subsequent R&D activities. Notably, planning R&D becomes less risky and more straightforward if information about, for instance, the growth rate of the AR technological development and most involved organizations is available.

So far, insights on the technological evolution of AR are mainly gathered in survey papers. Among them, some are focused on specific technical aspects and related shortcomings [111]–[116], while others are focused on research evolution and future trends [117]–[119], thus limiting the comprehensiveness of the analysis of the AR domain and the provisions of managerial and policy implications. Moreover, despite the important attempt to fully trace the AR domain, some of the most noteworthy papers reduced the search scope to articles published in past conferences [117], [118] or provided an overview of the solutions already in use [119]. Hence, these studies leave out some data useful to uncover all the technologies developed, including those that are yet to be adopted. On the other hand, to overcome these issues, recent works analyze patent dynamics in AR [120], [121], hence proposing a novel approach to study technological trends based upon patented technologies, being these more representatives of solutions developed in a given domain [122]. In the present research, we rely upon these studies, offering however a more reliable and comprehensive investigation. Indeed, we manually processed each patent instead of using a computer-based classification approach. We believe that given the multi-topic nature of the AR patents, it becomes necessary to dig into each patent in order to understand the type of patented technology. Moreover, we update and complement prior analysis by including aspects not previously addressed, such as geographical trends and assessment of highly impacting organizations, which may provide additional valuable information to comprehend where the AR domain is and where it may go. In line with this reasoning, this study aims to understand the technological trends of AR, their temporal trends, the main technological areas, the geographic location of the technological developments, and key organizations involved in the AR domain, with an emphasis on those developing highly impacting AR solutions.

In this chapter[3] we will we study and analyze a sample of 2,373 granted patents filed at the USPTO in the period 1993-2018.

4.1. Conceptualizing AR Classification

As already discussed in Chapter 1 AR requires three fundamental technologies:

- Display system;
- Tracking system and
- Interaction system.

---

[3] The results of the studies described in this chapter were published in the following paper: Evangelista, A., Ardito, L., Boccaccio, A., Fiorentino, M., Petruzzelli, A. M. & A. E. Uva. (2020) Unveiling the technological trends of augmented reality: A patent analysis. Computers in Industry, Volume 118.

Based on this we can create the three technology classes:

- The **display** class includes visual displays and nonvisual displays;
- The **tracking** class includes systems that perform the virtual object registration in a real environment;
- The **user interaction (UI)** class includes a specific branch of HCI research, uses alternative means to traditional 2D user interfaces such as a mouse, keyboard, and touch screen input.

Furthermore, two additional classes can be considered to account for those solutions —the integrated AR systems [123], [124]— that include the three main (stand-alone) technological classes. Indeed, an AR system may be specific for an application field or pervasive in nature, i.e., with no application in any specific field. In detail, the two classes can be defined as follows:

The **application** class includes existing solutions and technologies that innovate in a specific domain of application. Nowadays, the increased interest of major technology companies with rising investments in AR technology is one of the major factors driving this market. Basically, the AR is exploitable in industrial [44], military [125], healthcare [126], entertainment [127], retail [128], and e-commerce applications [129]. For instance, AR in the enterprise is taking off also pushed by the Industry 4.0 emerging paradigm, where it is exploited for training personnel, maintenance of machines, design, engineering simulations and safety [130]–[133]. In healthcare and medical fields, AR can be exploited, for instance, in case of surgery, for visualizing medical data (conventional x-ray, computed tomography, and so on) directly superimposed on the patient [134], thus allowing the surgeon to conduct a minimally invasive surgery [135]. Moreover, AR lends itself well for training doctors and medical students [136]. Nevertheless, the AR market will be driven by consumer applications such as gaming, sports, and entertainment [137]. Among them, the greatest commercially successful AR game experience is Pokémon GO, with over 100 million downloads [138], which uses AR for attracting potential consumers into malls and shops by leveraging gamification dynamics.

As regards the aforementioned classes, they can be also recognized in classifications made by previous studies. The survey by Zhou et al. [17], in pointing out the technology areas needed to deliver an AR application, identifies five primary topics: Display Techniques, Interaction Techniques, Tracking Techniques, Calibration and Registration, and AR Applications. According to Schmalstieg and Hollerer [139], tracking, calibration, and registration techniques overlap in practical use, hence reducing the actual number of areas to four. These four areas are recalled by our classification, where the class named tacking includes tracking, calibration, and registration techniques as suggested by Schmalstieg and Hollerer.

Finally, the **system** class includes integrated AR solutions [140] that are innovative because exploit existing AR technologies in a novel way but are not specifically designed to be adopted in various industry domains. In other words, they are more pervasive in nature. Basically, we added the remaining class—system—in order to classify patents that describe the implementation of display, tracking, and user interaction technologies in a single system [140], and that, as such, cannot be included in any of the other classes.

The final classification, including the five classes, is reported in Fig. 20 .

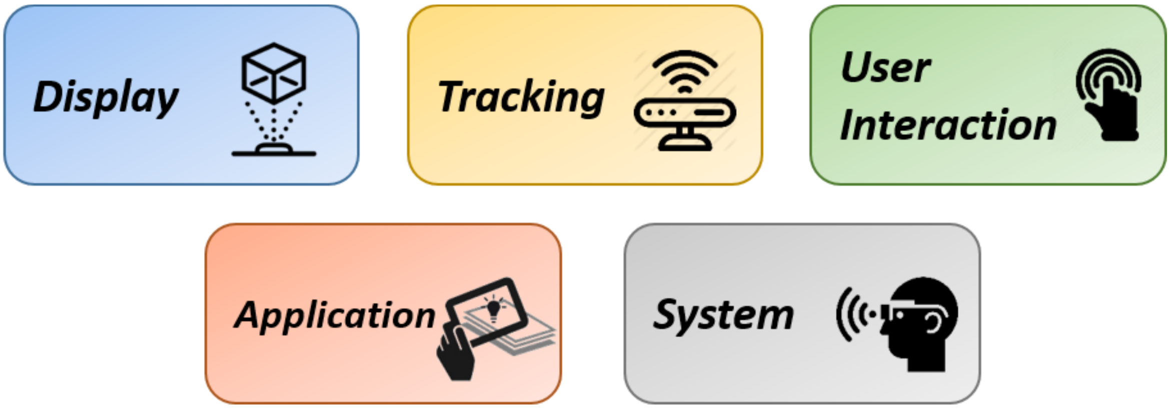


Fig. 20 Classification of AR

4.2. Patents as a Mean to trace Technological Trends

A patent is recognized as an intellectual property (IP) right that allows an organization to solely use and exploit its invention. In turn, patenting prevents others from commercially using the invention, establishes the inventing organization as a preeminent player in the market [141], [142], and makes business partners, investors, and shareholders perceive the inventing organization as technologically advanced and worth of financing (e.g., [143]).

These very well-known aspects of patenting mainly relate to the managerial practices and have largely been studied by the IP literature [144], [145]. Instead, rooted in the characteristic of patented inventions to be novel, non-obvious, and useful , the technology management literature has looked at patents with a different perspective. That is, regardless of their actual effectiveness as an IP tool, since patents reflect inventions that must possess the characteristics, they have been deemed to assess R&D efforts. Specifically, a wealth of research has sought to validate patents as a proxy for tracing developed technologies and, nowadays, patents represent the most common proxy for R&D outputs [146]–[152].

Specifically, given the variety of information of patent documents – e.g., filing and granting dates, name(s) and residence of inventor(s), name(s) of assignee(s) and location of headquarter(s), technological classifications, and citations – multiple aspects of technological trends (e.g., temporal trends, geographical distribution, and patent quality) can be assessed. In line with this reasoning, a number of studies have agreed with the suitability of patents for analyzing technological trends in a comprehensive manner (e.g., [153]–[156]), including the fields related to computers in industry. For instance, studies on the convergence of ICT technological standards [157] and cross-country comparisons for studying the antecedents of ICT solutions [158] have relied on patent information. Moreover, patents have been used to provide a comprehensive picture of the technology lifecycle of telematics [159], derive policy and managerial implications for future R&D activities in the IoT domain by mapping related patenting activity trend, and inform about technologies enabling supply chain management-marketing integration in light of the Industry 4.0 revolution .

4.3. Methods and Data

To analyze the technological trends of AR, we collected granted patents related to the AR domain. That is, we excluded patent applications whose review process is still ongoing since the respective invention cannot be still considered an actual patent even though information about the potential future patent is available. To collect patents, firstly, the search string "augmented reality" was defined. Then, we queried the USPTO for granted patents that contain this search string in the title, abstract, or claims - the resulting query string, hence, was: [TTL/"augmented reality" OR ABST/"augmented reality" OR ACLM/"augmented reality"], where TTL refers to the field title, ABST refers to the field abstract, and ACLM refers to the field claim(s). Indeed, if the search string appears in the title or abstract, it is more likely that the patent actually pertains to the domain described by the search string. Likewise, we also considered the claims since a claim mentioning "augmented reality" would suggest that the patent protects a feature/application related to AR [160], [161]. Other fields, such as the description, have been excluded since they are more generic and/or used for discussing macro-trends that do not specifically pertain to the searched string, thus leading to non-relevant results. This approach is consistent with many previous studies adopting patent analysis for examining technological trends (e.g., [162], [163],[164]), and its reliability was formally confirmed by Xie et al. [165], who addressed the effectiveness evaluation of keyword search strategy for patent identification, revealing that “the most effective method of identifying patents in a specific domain through keyword search is using the patent information in the title, abstract and claims”, as this is where an invention's essential content is described” (see also [166]). The USPTO was chosen as patent source of patent data because it “represents the largest body where patents are filed from all over the world” [77]. Moreover, it “is supposed to have one of the lowest home biases as more than 50% of the patents that are issued in the U.S. goes toward non-U.S. entities” [78,79]. This lets us consider the USPTO without the necessity to scrutinize all other patent offices, still allowing us to provide a more comprehensive picture of the AR technological development. The search process ended on April 30, 2019. Initially, the search process yielded a sample of 2,587 patents. To avoid false-positive results, each patent was read by three AR experts, together with the author of this dissertation, and based on the exclusion criteria reported in Tab. 9, noise patents were eliminated from the starting sample. The final sample is composed of 2,373 granted patents filed between 1993 and 2018. According to the classification, selected patents were distinguished among our 5 classes.

Tab. 9 Exclusion criteria.

Exclusion criteria	**Examples of excluded patents**
The patent title and abstract describe a technology not related to AR and, in the claims, the term “augmented reality” is present but used in a generic way and not well addressed.	[168], [169], [170]
The patent title, abstract and claims describe a technology using the term “augmented reality” but was virtual reality.	[171], [172], [173]

This section explains more in detail the analysis that we will propose in the next section, and how patent information has been used to deliver our analysis. First, we will present temporal trends of R&D efforts in general and for each specific AR class. Patent count per year is used as the measure for the R&D outputs undertaken over time. Second, the geographic origins of the developed patents will be presented. Each patent was assigned to a country based on the country where the first inventor resides. Indeed, the first inventor is considered as the main inventor, and the inventing activity usually takes place where s/he resides [153]. Third, analysis at the organizational level was conducted. Accordingly, we will highlight the organizations more involved in the development of AR patents. In this case, inventing organizations are assessed in terms of both patent count and impact on subsequent patents. Following previous studies, the impact of inventing organizations is measured by means of forwarding citations, i.e., the citations received by an organizations' patents from patents developed afterward (e.g., [152], [174]).

4.4. Results

In this section, we begin to look at the AR patent landscape and perform an analysis of temporal trends, geographical trends, class distribution, and inventing organizations.

4.4.1. Temporal Trends

Fig. 21 shows the patenting activity trend of the 2,373 collected (granted) patents respect to both their filing year (which better reflects the actual year of development of inventions) and granting year (which reflects the year when the property right is actually granted). In other words, the two trends depict the temporal distribution of the same sample patents. All in all, the patenting activity of AR solutions began in 1993. Looking at the temporal distribution respect to the filing year, the patenting activity trend remained quite constant until 2007, while it had a sharp growth in the number of patents from 2008 onwards. This sharp increase in the number of patents is reflected with a 3-4 years lag, as revealed by the patenting activity trend respect to the granting year. Accordingly, it manifests a sharp growth from 2011 onwards. This implies that patents require 3 to 4 years to be granted. Thus, patents filed in the last years (i.e., 2016-2018) are likely to be not granted yet, meaning that they are not captured by our analysis. This explains the apparent declining trend starting from 2015 when looking at the patenting activity trend respect to the filing year. That is, the declining trend is more the result of a long review process than a reduction of R&D efforts in that it is uncommon that patents filed more recently are granted in less than 1-3 years. This can be further proven by looking at the patenting activity trend with respect to the granting year. This trend is, in fact, steadily growing until 2018. Specifically, the annual percentage growth rate of the number of patents was minimum 35% and maximum 227% - 82% on average - in the time period 2012-2018 (granting years). The limited number of patents granted in 2019 is due to the fact that our search process ended at the end of April 2019.

These trends can be widely explained by the fast development of mobile technology in the last decade. In fact, 2008 has originated a wave of new AR-satisfying device, for instance, the first multi-touch screen mobile phone also known as Apple iPhone or also the Android-based G1, the HTC's Touch HD, the Nokia N97 and so on. Furthermore, in 2007, the first AR tracking SDKs for mobile devices were released by ARToolKit [175]. In the following year, these tracking libraries were released for the main mobile operative systems (OS) such as iOS in 2008 and two years later, in 2010, it was made available an Android version. From this point on, a large series of mobile devices have been presented, and many of them are able to support AR applications. However, we believe that from 2009 onwards the development of AR technology is mainly driven by high expectations and huge investments from world-leading companies such as Microsoft, Sony, IBM, Google, Qualcomm, and so on.

In Fig. 22, we show the temporal trend from 1992 onwards of the scientific documents published in Scopus. In the previous graph, we found a significant and growing interest in AR patents since 2008 (considering the filing year), but in the scientific publications, the interest towards AR has broken out since 1997. In fact, one of the most cited AR paper was published in 1997, that is "A Survey of Augmented Reality" by Azuma [5]. This paper describes the AR technology and the first application attempts in different fields; furthermore, it defines the AR system and their characteristics, summarizing them in 3 pillars.

Thus, we also believe that the growing patenting activity trend from 2008 onwards is mainly driven by strong scientific activity made in the previous years in the AR field, and from which patenting activity has benefited successively. However, scientific research in the AR field has temporal growth, in terms of publications number, always positive. The graph also shows the trend of journal articles published from 1992 onwards. Noteworthy is the rapid growth in the number of publications since 2016. This acceleration of the growing trend is probably due to the release of Microsoft HoloLens (March 2016), the holographic HMD running Windows Mixed Reality platform, which represents a new publishing opportunity for researchers who want to exploit the HoloLens features for new AR applications or just to highlight strengths and weaknesses.

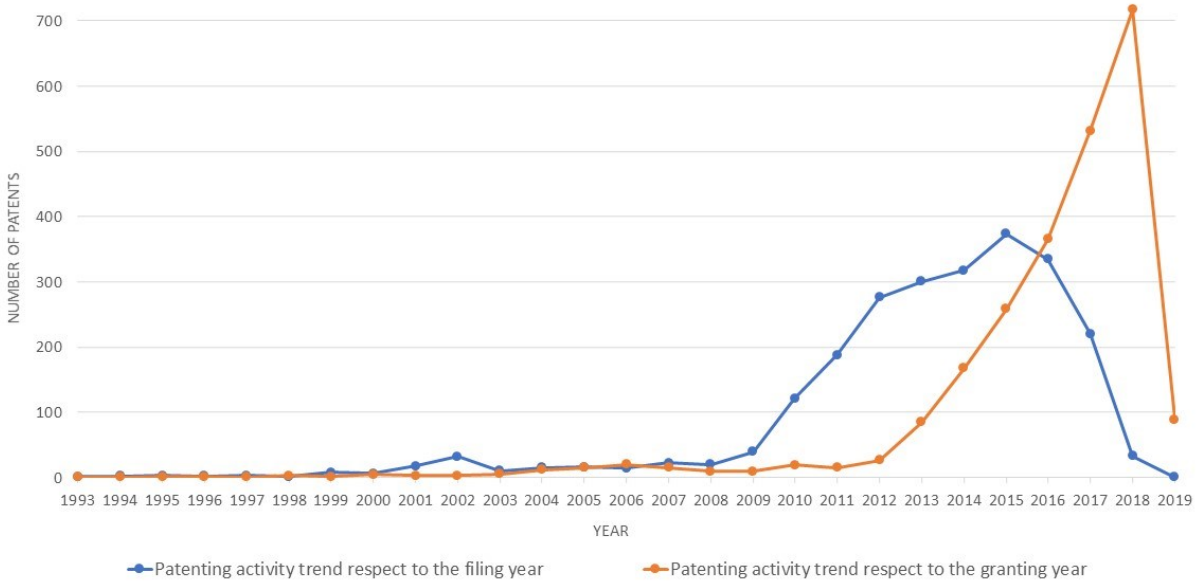


Fig. 21 Temporal trends per filing and granting year show a sharp increment in AR patent activity from 2008 onwards.

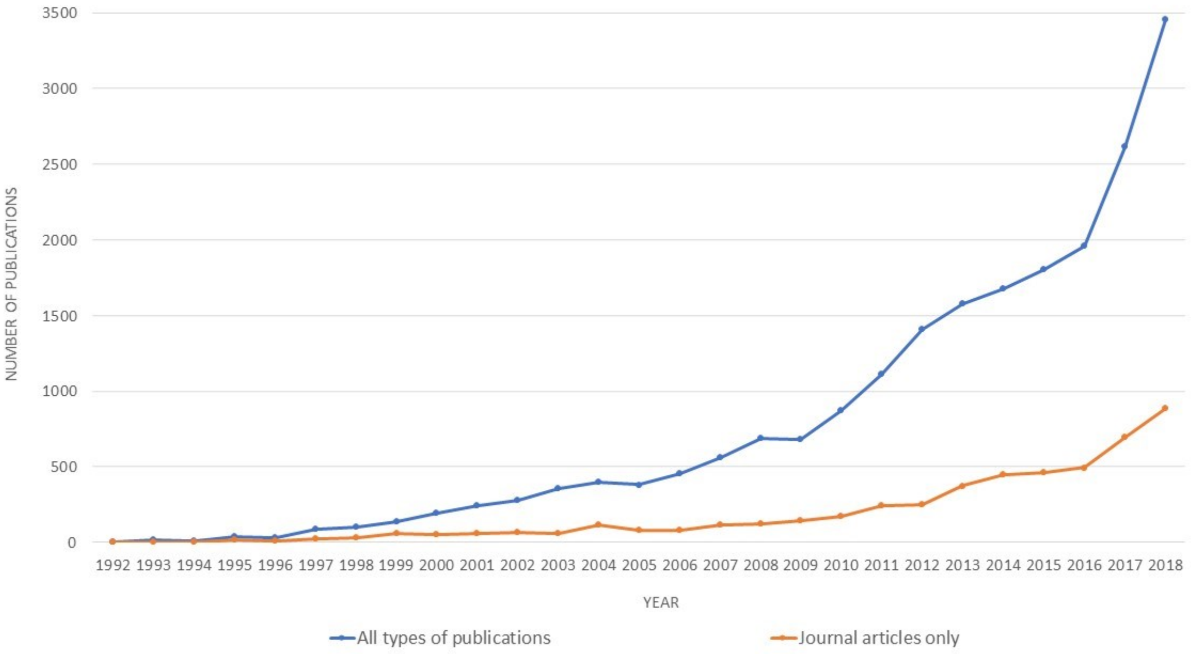


Fig. 22 The trends of scientific documents published in Scopus database show a growing interest in AR from 1997 onwards.

4.4.2. **Geographical Trends**

We examined the global geographical distribution of granted patents across world continents in the AR field, in order to highlight the geographical area that contributes the most to the technological development in the AR domain. From the pie chart in Fig. 23, we note that the main geographical area to which patents can be associated in North America (68%). A minor but not negligible role is played by Asia (18%) and Europe (13%). Fig. 24 disentangles the contribution of each geographical area (North America, Asia, Europa, and Others) to the overall patenting activity trend presented earlier in Fig. 21. The distinct patenting activity trends are plotted with respect to the filing year. The Fig. 23 shows a sharp growth of the number of patents filed in 2008 onwards in all geographic areas, but especially in North America. This trend can be explained by a large number of milestones placed by the United States (U.S.) during the previous 50 years in AR development. All the know-how acquired in these five decades, also thanks to the economic policies of the U.S. government in the industrial, academic, and military research fields, was stored and used to carry out an intense patenting activity. As a matter of fact, in 1968, one of the first attempts to create an AR system was made in the University of Utah by Ivan Sutherland [176] and many years later, in 1992, Tom Caudell and David Mizell used an HMD see-through for implement an AR prototype system for U.S. airplane manufacturer: the Boeing Company [177]. In 1997, Feiner et al. [161] presented the Touring Machine that is the first mobile AR system (MARS), made at Columbia University. Two years later in 1999, Kato and Billinghurst presented ARToolKit [178], a pose tracking library with six degrees of freedom based on square fiducials marker and a template-based approach for recognition. These are just a small set of milestones placed by the U.S., a more exhaustive list can be found in [179].

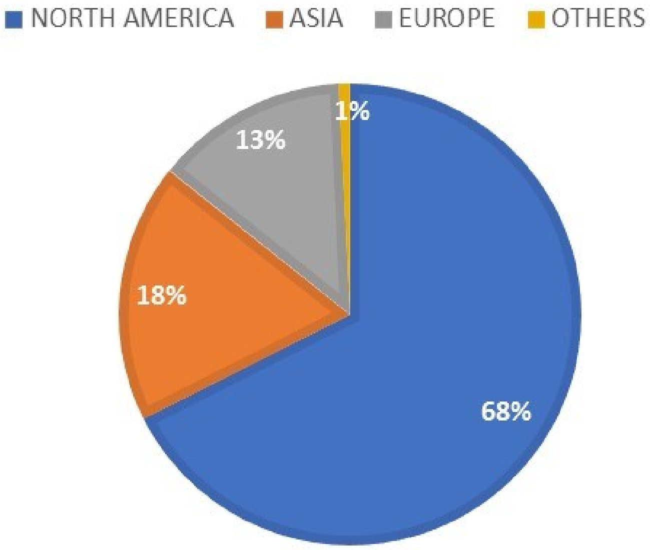


Fig. 23 Geographical distribution of granted patents shows that North America driving the AR innovation.

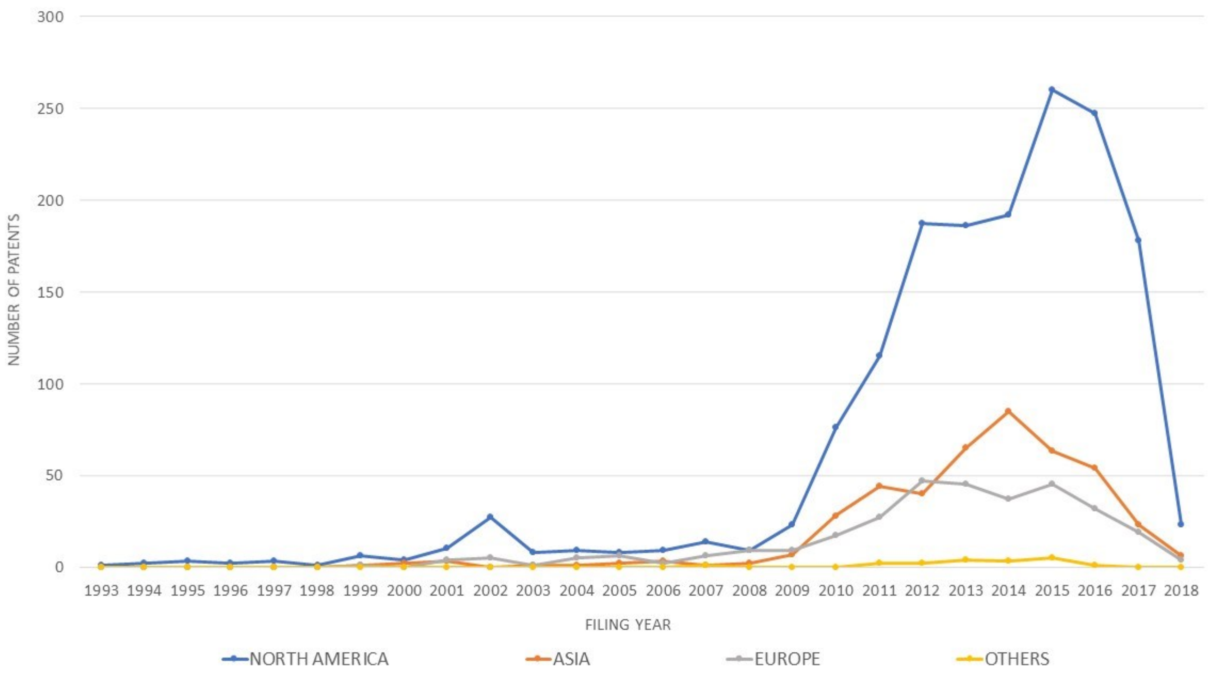


Fig. 24 Geographical distribution of granted patents per filing year shows that, from 2008 onwards, the patent activity of North America is the most intense.

Fig. 25 reveals the top six states in terms of granted patents in Asia, like South Korea, Japan, Israel, Japan, China, and India. In particular, South Korea (43%) and Japan (25%) have developed more than half of all Asian patents. Furthermore, the contribution of Israel (13%) to the Asian patenting activity is not negligible. Differently, the contribution of China and India is scant (6%). It is yet interesting to note the 5% contribution of Taiwan. In Fig. 26, we delved into the geographical distribution of patents in Europe. The United Kingdom (35%) owns most of the European patents, followed by Germany (20%), France (11%), and Finland (9%). Despite the push of Industry 4.0 policies, European numbers remain low when compared with those of North America and Asia (see Fig. 25).

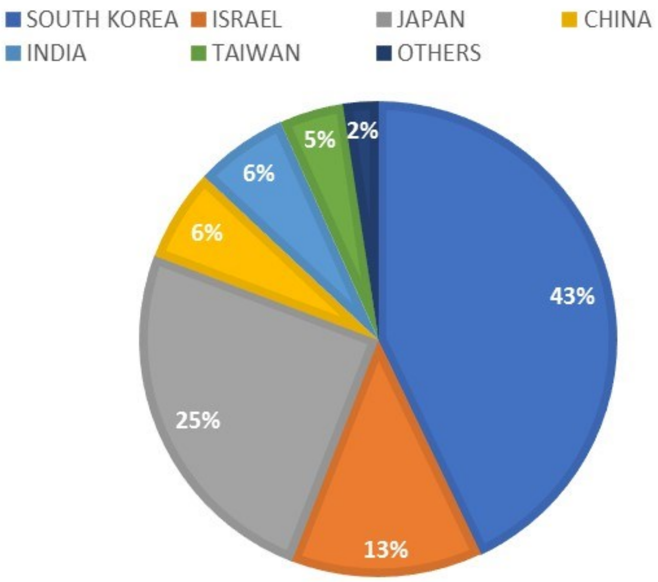


Fig. 25 Geographical distribution focused on Asia shows that South Korea driving the AR innovation.

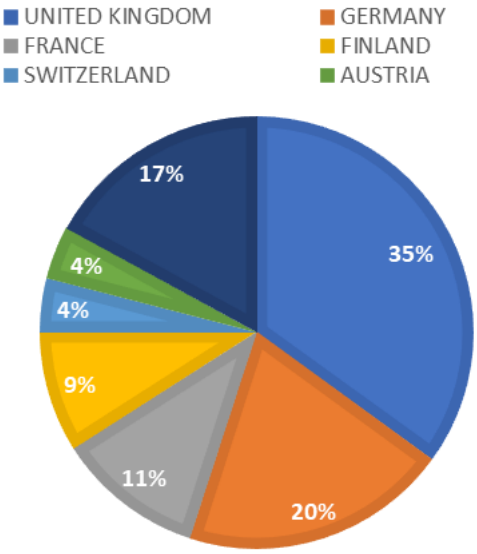


Fig. 26 Geographical distribution focused on Europe shows that the United Kingdom and Germany own most than 50 % of European AR innovation.

4.4.3. Classes Distribution Analysis

Fig. 27 shows the percentage dimensions of each one of the patents' classes. The numerousness of each class population can be explained considering both technological and economic motivations.

The most populated class is system (39.23%). This finding can be explained by the fact that this class is very broad [180], [181], but it could also be argued that in this field, where many established technologies already exist, integrating existing ones into new systems is generally less prone to unsuccess than the development of new ones.

The amplitude of the application class (21.53%) can be explained because some application fields are drivers of AR (e.g. manufacturing, medical, entertainment and so on). Indeed, these are the fields where AR has been proved to be particularly effective by the academic and industrial literature [57], [182]–[184].

The third class is display device (14.59%). Since the first development of AR, visual displays were considered one of the most critical aspects of this class [91]. Despite the great development efforts, modern visual displays, especially HMD, have still many limits in terms of field of view (FOV), ergonomics, cybersickness and so on [185]–[187]. It is worth noting that not only visual displays are patented for AR (e.g., haptic and audio [188], [189]).

The fourth class is tracking (13.78%). Similarly to display technologies, tracking technologies are one of the open challenges of AR [11]. A precise alignment of virtual elements in the real environment is a crucial aspect for a satisfactory user experience [190]. There are several patents of tracking techniques in the field of AR divided into vision-based tracking, sensor-based tracking, and sensor fusion tracking [191], [192].

The user interaction class is the least populated (10.87%). Indeed, designing AR interactions is not an easy task, especially when interaction must take account of the inclusion of the user's physical surroundings as part of the interface. Furthermore, UI design is strictly related to the application scenario. The UI class encompasses several patents involving both novel interface technologies and interaction metaphors allowing the user to interact with the augmented scene [193]–[195].

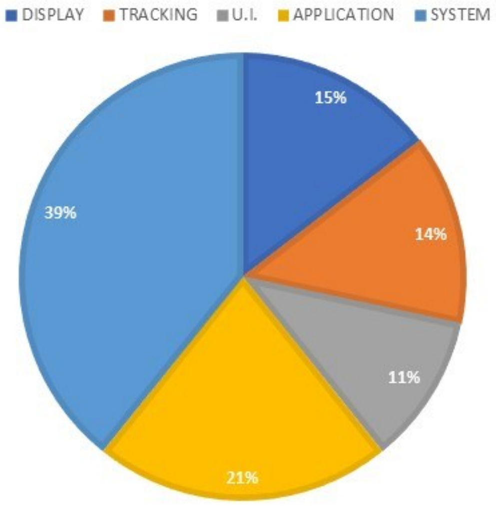


Fig. 27 Classification of patents per AR classes shows that system and application are the most patented classes.

Fig. 28 further illustrates how the R&D efforts of the different AR classes are evolving over time. In particular, the class of system shows the highest growth rate, with a growth trend starting one year before the others, from 2008 onwards. The application class is growing rapidly from 2009 onwards with a slight decline in 2014 and a recovery in the successive years. The trends of the other 3 classes (Tracking, UI, Display) are characterized by a moderate growth starting from 2009 with a fluctuating trend. The display device class since 2013 has a fast growth in terms of patents filed.

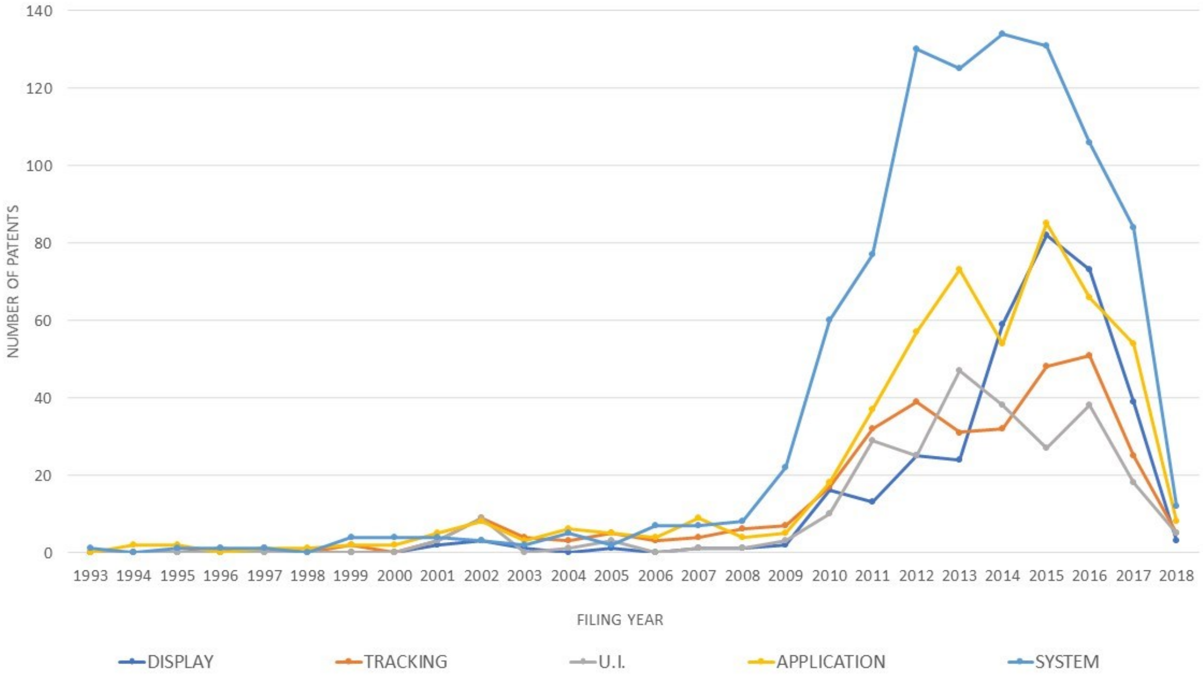


Fig. 28 Temporal trends of patents per AR class confirm 2008 as a turning point for AR patent activity, especially for System class.

The AR application class includes all patents that provide innovation in a specific domain. Therefore, a further sub-analysis was made at the level of application domains to unveil which specific domains are covered by the sample patents and to what extent. In so doing, the 13 classes identified by Mekni and Lemieux [119] were considered, namely Medical, Military, Manufacturing, Visualization, Entertainment and Games, Robotics, Education, Marketing, Navigation and Path Planning, Tourism and Cultural Heritage, Geospatial, Urban Planning and Civil Engineering. Still, Mekni and Lemieux acknowledged that their classification might not be exhaustive. Accordingly, we extended their classification with an additional domain that emerged during the patent analysis, namely Banking. Fig. 29 delves into the specific domains covered by the application class. The domains Entertainment and Games (103 patents), Navigation and Path Planning (95 patents), Manufacturing (77 patents), Medical (64 patents), and Marketing (54 patents) include almost 80% of all patents in application class. The remaining

20% is divided among the other 8 domains. where Military, Geospatial, and Tourism and Cultural Heritage are the domains with the lowest R&D efforts placed on, probably due to the scarcer commercial opportunities for AR solutions in these application domains.

Fig. 30 shows the temporal trend of R&D efforts in the different application domains of the AR. The application domain Entertainment and Games has been growing rapidly since 2008, with a slight decrease in 2014 and a recovery in the following years. It is worth noting that Navigation and Path Planning has a similar trend to Entertainment and Games but from 2010 onwards. The Manufacturing application domain has a slow growth until 2015, but in the same year, it is the most patented application domain. Medical and Marketing are characterized by moderate growth from 2010 with a fluctuating trend.

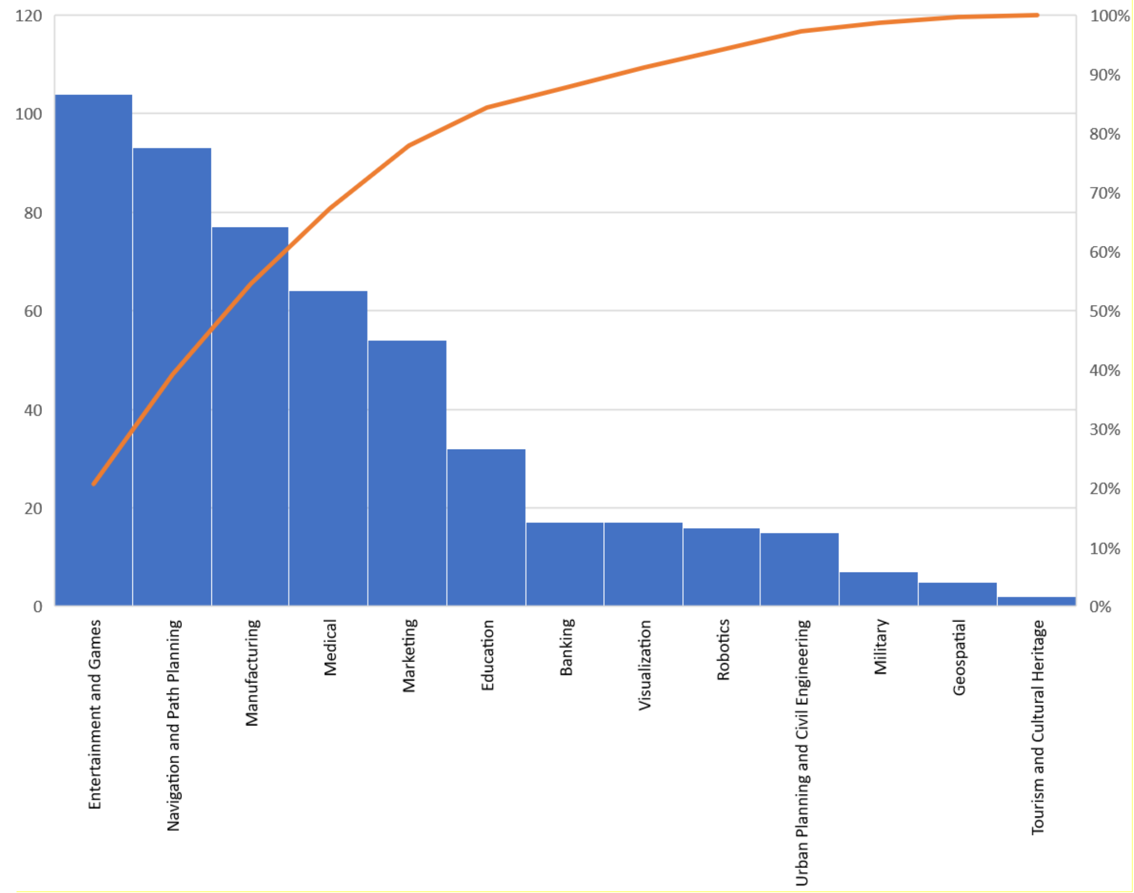


Fig. 29 Domains distribution within the application class. The Pareto chart shows that the five out 13 domains account for almost 80% of the patents of the application class.

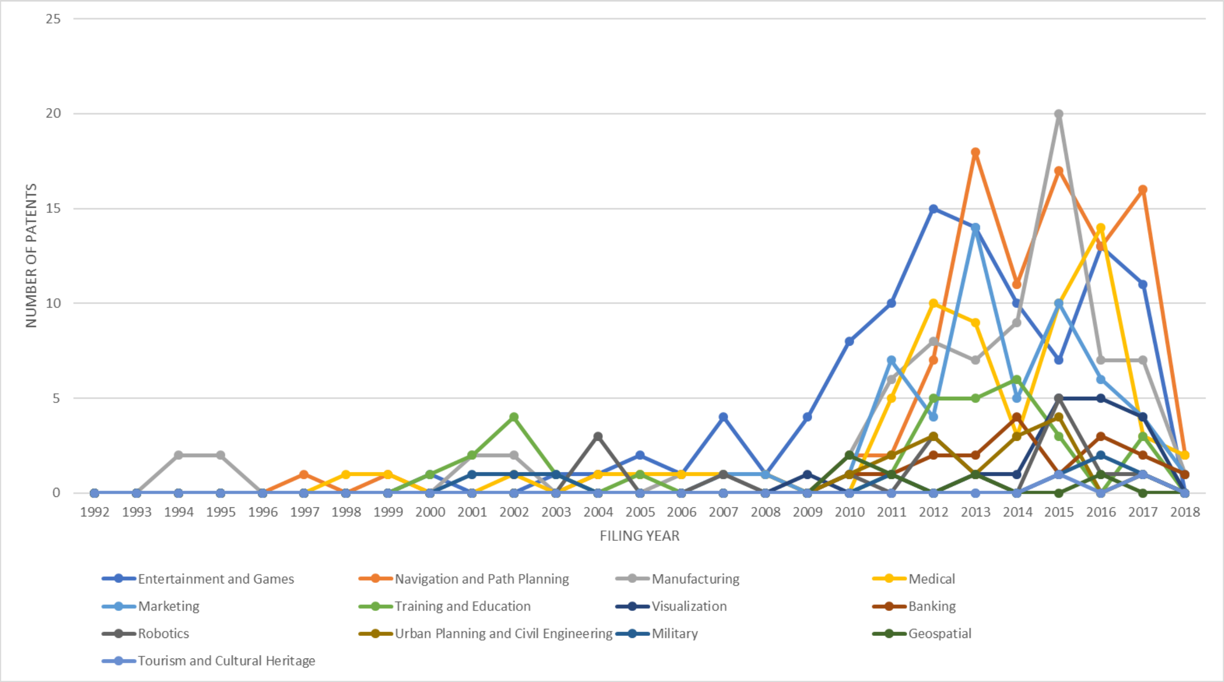


Fig. 30 Temporal trends of application domains distribution show that the first domain to grow appreciably is Entertainment and Games.

4.4.4. **Organization Distribution**

In Fig. 31 are shown the top 10 patenting organizations. Microsoft Corporation (U.S.) (29%) is the most active in the AR domain, followed by Sony (JP) (10%) and IBM (U.S) (10%). Below 10% there are Qualcomm (U.S.) (9%), Samsung Electronics (S.K.) (8%), Magic Leap (U.S.) (7%), Amazon Technologies (U.S) (7%), Intel Corporation (U.S) (7%), Empire Technology Development (U.S.) (7%) and Daqri (U.S) (6%). It is worth noting that only companies are included in the top 10, which means their influence on AR, from a quantitative perspective, is higher than universities, research centers, and government organizations. In particular, eight companies out of 10 are headquartered in the U.S., further supporting the findings of Fig. 29 and Fig. 24. Fig. 30 complements Fig. 29 by revealing when those companies patented their inventions. It shows that the top 10 patent-intensive organizations have not contributed to AR since the beginning of the emergence of AR patents (1993) but started around the late 2000s. Notably, the oldest patent is by Intel Corporation, filed in 2002. This can be explained by the fact that R&D efforts in the AR domain likely started to become a less risky investment in those years due to improved awareness about AR by enterprises, the (call for the) implementation of digitalization strategies, and government support.

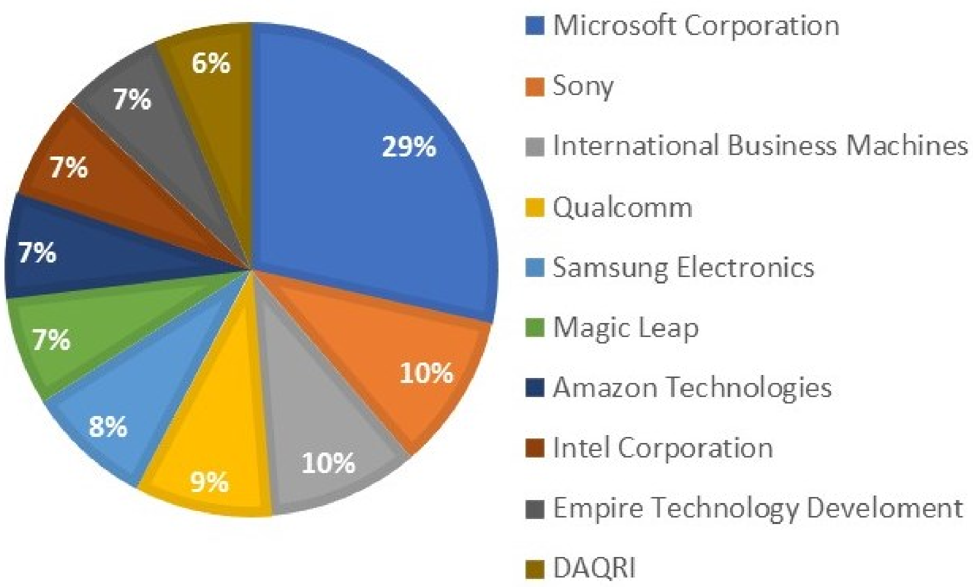


Fig. 31 The chart of top 10 patenting organizations distribution (extracted from Table 1 in appendix) shows the Microsoft Corporation leadership in patent activities.

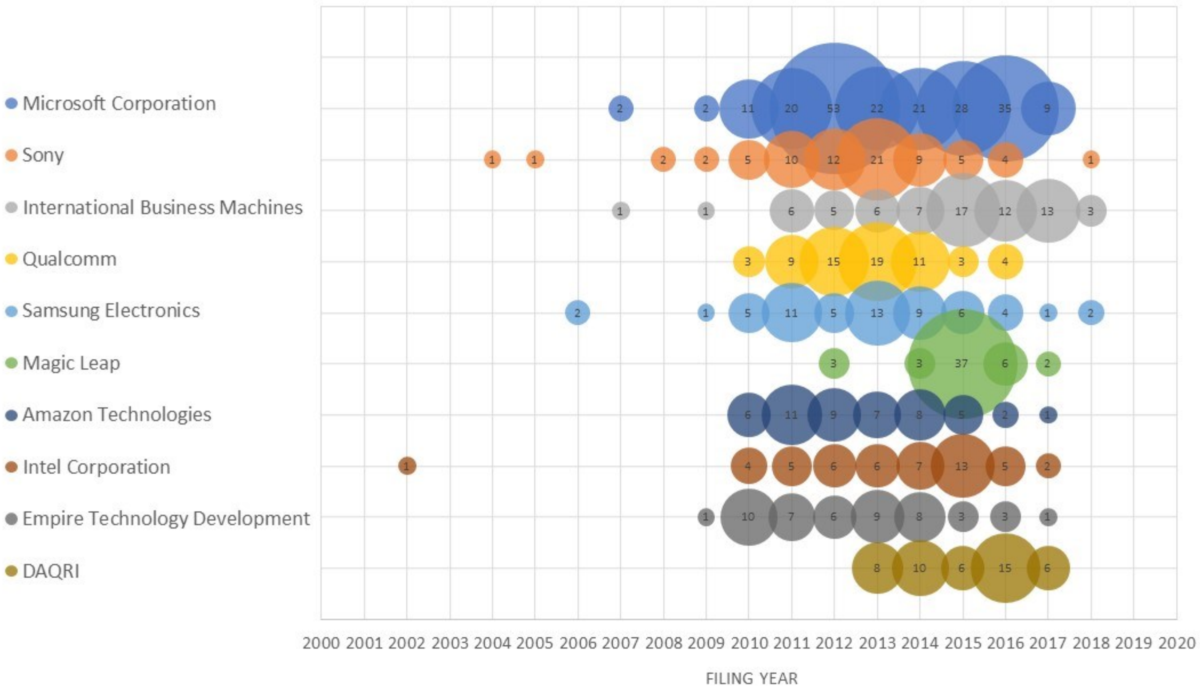


Fig. 32 Patenting activity trends of the top 10 patent-intensive organizations (number of patents in the bubble).

We also ranked the companies respect to the number of citations received by their patents. In other words, we identified the top 10 highly impacting organizations. Fig. 31 and Fig. 32 reveals that U.S. (with Microsoft Corporation, University of North Carolina, Google, Criticom corporation, Geo Vector, Information Decision Technologies, Amazon Technologies and HRL laboratories) and German (with Siemens and Metaio) organizations hold the majority of patents with the highest technological impact. This stresses the dominance of the U.S. area and highlights that the technologies developed in Asia and Europe are, probably, the result of more incremental R&D efforts with no sensible impact on subsequent R&D. It is also interesting to highlight that most patent-intensive organizations are not necessarily those that have a considerable impact on subsequent R&D activities. In fact, only Microsoft Corporation and Amazon Technologies are present both rankings. Moreover, when considering the rank of patenting organizations respect to their impact, universities, research centers, and government organizations assume more relevant positions. For instance, the University of North Carolina is even one of the top 10 highly impacting organizations as revealed from Fig. 33.

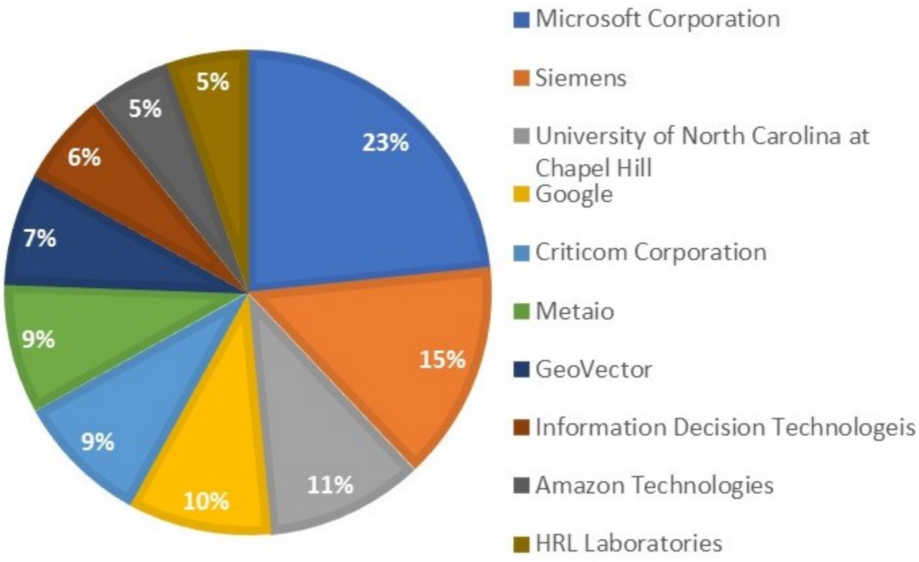


Fig. 33 The chart of top 10 patenting organizations per received citations shows that only Microsoft Corporation is also the organization that owns the largest number of valuable patents.

4.5. Discussion of Results

This work unveils the technological trends of the AR domain. Specifically, this work tries to explain the technological development of AR by revealing temporal trends, geographical distribution, and most involved organizations in AR patenting. To do so, we collected 2,373 AR granted patents filed between 1993 and 2018 at the USPTO. In line with previous studies, we categorize these patents into five main technological classes, namely display, tracking, UI., application, and system. Despite the intrinsic complexity of the AR domain, we believe our work provides some valuable results from which AR scholars, managers, and policymakers could benefit.

From a theoretical perspective to the best of our knowledge, this study is one of the first attempts to depict a comprehensive overview of AR by exploiting patent-based measures. In detail, such an overview may benefit AR scholars in identifying the extent and pace at which actual technologies have been developed in the AR domain, both in general and considering (five) different AR classes. In this way, they may be in a better position to understand where more basic research is (still) needed and where research on concrete applications can be proposed.

From a managerial and policy perspective, firstly, the growing trend in patenting activity, especially from 2008, should be considered by managers as a signal (and confirmation) of the increasing expectations about AR from the business point of view. This is corroborated by the fact that most of the developed AR patents are owned by private organizations, hence indicating the central role of profit-oriented organizations as catalysts for R&D efforts in the domain under investigation. Nonetheless, the growing trend is quite recent since it started a decade ago. Thus, it is likely that there is still room for those firms seeking to enter the AR market, but they should not wait too much since the fast growth rate. Second, managers and policymakers are advised of the geographical origins of the technological knowledge underlying AR. From this perspective, it is evidenced by the overwhelming primacy of North America, especially of the U.S. (Canada contribution is negligible). Instead, Europe lags behind the U.S. and, also, the Asian context, which, driven by South Korea and Japan, is the second most patent-intensive geographical area. This implies that the U.S. may be considered the key area from which sourcing technological knowledge and learning about AR. The most highly impacting organizations are headquartered in the U.S. In turn, it could be said that the U.S. market is fuller than European and Asian ones, which may represent better contexts were running new businesses in the AR domain. Notwithstanding, firms operating (or attempting to enter) in such contexts should not disregard a closer look at the U.S. context, since it may be their reference framework. From a policy perspective, European policymakers should account for the fact that despite AR has been indicated as one of the keys enabling technologies, the European context is not even as productive as the Asian one. Maybe, incentive schemes and/or financial support to R&D activities towards AR should be reinforced. Also, collaboration efforts between European and U.S. organizations should be promoted in order to improve technological catch-up and learning activities.

Third, our findings show the differences existing between the AR classes under analysis. System is the class with the most intense patenting activity, so it reflects that the majority of R&D efforts are directed to the development of pervasive systems. The Application class is the second most patented class, and this could mean that AR has demonstrated enough (potential) success in some specific application domains to make the AR worthy of being patented in these specific fields. Specifically, the domains that have manifested the highest R&D efforts are Entertainment and Games Navigation, Path Planning, Manufacturing, Medical, and Marketing, covering 80% of the patents in the application domain. These hence represent the most exploited markets so far with regard to AR solutions. In this context, managers should investigate whether and to what extent there exist further opportunities in these markets as well as whether and to what extent investments in less exploited - and hence lees competitive - markets are worthy to be explored or not, especially considering that some of these markets are at the core of the digital revolution agenda (e.g., Robotics, Tourism and Cultural Heritage, Urban Planning and Civil Engineering). The three stand-alone AR technological classes (Display, Tracking, UI), together, include less than half of the total patents. This result may have a double meaning: (i) the development of a new technology in these three classes is very risky, due to the fact that established technologies with which it is difficult to compete already exist, hence driving the majority of R&D efforts towards the development integrated AR solutions (system and application) rather than the improvement of a specific (stand-alone) solution; (ii) the technologies are rather mature, but that they still need improvements. Finally, looking at the most patent-intensive organizations, it emerges that public research organizations and universities seem to play a marginal role. Indeed, as highlighted, firms represent the organizations that own many of the patents. However, this result (slightly) changes when organizations are ranked according to their impact. In this case, universities rise in position; for instance, the University of North Carolina at Chapel Hill ranks third. Therefore, executives must be aware that, probably, universities are actually driving the path of the AR domain even though, in absolute terms, their contribution may appear less evident. Some of the limits in current AR solutions for the industry may suffer from this misalignment. That is, firms, in order to avoid risky projects, do not explore for more radical solutions, even though existing ones appear not so effective for the industrial practice. Conversely, universities are more devoted to this exploratory approach. In turn, policymakers, in light of this finding, may design actions aimed at fostering collaborations between firms and universities, which will likely benefit AR from the cross-fertilization of their different perspectives and avoid the technological lock-in often characterizing firms' R&D efforts. Furthermore, the highlighted difference between Fig. 28 and Fig. 31 may help distinguishing organizations respect to the relevance of their R&D efforts. For example, it emerged that Microsoft Corporation stands out both for the number of patents granted and for their impact in the AR field. This helps managers in recognizing which organizations may be more harmful, from a competitive perspective, or beneficial, from a collaborative perspective. Likewise, policymakers may more easily identify organizations that are having the highest impact in the AR domain and could accordingly further stimulate their research productivity.

Fourth, although AR technology is increasing in expectations due to technological progress in hardware and software, it still suffers from technical and non-technical limitations that currently limit its use in everyday life. From a technical point of view, the limitations are mainly due to several challenges, such as alignment, interaction, and visualization [11]. Despite the important role that the three main AR technologies (visualization, tracking, and interaction) play in addressing these challenges, as our results show, less than half of the total patents belong to these classes. In light of these considerations and in our opinion, research and innovation efforts should be more focused on the aforementioned classes in order to overcome these still open challenges in AR. The limitations in the use of AR are not only technical but also human, in fact, there are factors such as social acceptance, privacy and usability problems that slow down the diffusion of AR in everyday life.

Of course, we acknowledge that these conjectures may be subject to the data source. The conjectures can surely well-describe the US market, which is also the biggest and most representative one with regard to AR. Nonetheless, despite we still underline the USPTO is the patent database where organizations worldwide tend to patent their invention a small country bias may persist. This may relax the validity of our implications, however calling for future studies to confirm (or contradict) our findings, for instance by examining PCT or triadic patent applications [196].

In conclusion, we believe that this study has taken the literature one step further in the on-going debate on the dynamics of AR technological solutions and hope that it may encourage further studies in AR trends analysis. We also expect that, in the future, it might be interesting to revisit this work to investigate the new trends and fast-changing landscape of the AR domain.

The lesson learned from this work puts us in front of clear choices, especially regarding the use of specific hardware to implement AR on application scenarios. As the patent analysis revealed, organizations such as Microsoft Corporation, Google, Sony, Samsung Electronics and Qualcomm are the ones patenting the most in the field of AR. For this reason, we decided to focus our attention on these organizations for the choice of hardware devices needed to implement AR in the Mill 4.0 industrial scenario.

With the end of this chapter, the discussion regarding the more theoretical aspect of AR ends. In the next chapter will be covered the part of implementation of AR in real industrial scenarios of Mill 4.0.

Chapter 5. Exploiting IAR for enhance the P&ID of a flour milling plant

In this chapter[4] we present an Augmented Reality (AR) application for handheld devices (HHD) that supports operators in information retrieval tasks in maintenance procedures in the context of Industry 4.0. During the doctoral program, the research carried out in this field aimed at exploiting such an AR visualization technology to enhance users in the comprehension of technical documentation.

In the specific case of Mill, plant information is traditionally conveyed through printed Piping and Instrumentation Diagrams (P&ID). For this reason, we developed an application that augments on a P&ID of the plant some virtual interactive graphics (hotspots) referenced to specific components drawn. Component data are retrieved, through a user interface, directly from the factory database and displayed on the screen. We evaluated the application through a user study aimed at comparing the AR application with the current practice, based on paper documentation, for an information retrieval task within a maintenance procedure.

As engineers and with our experience in the industrial field, we noticed that printed P&ID have the disadvantages to convey limited information by means of graphical signs. Such information is static (its update requires a new drawing by a field expert), is easily understandable only by a limited number of expert operators and is limited to the topology of the machinery. In this application scenario, information retrieval by means of the P&IDs it is a cumbersome task. For instance, if the operator needs the machinery model, the location and the maintenance record, s/he must, in sequence: identify the machinery on the P&ID, read its unambiguous plant-id, identify the corresponding machinery model and its location inside the plant, and, finally, retrieve from the machineries-documentation archive the maintenance records.

---

[4] The results of the studies described in this chapter were published in the following paper:
Gattullo, M, Evangelista, A., Uva, A. E., Fiorentino, M., Boccaccio, A., Manghisi, V. M. (2019). Exploiting Augmented Reality to Enhance Piping and Instrumentation Diagrams for Information Retrieval Tasks in Industry 4.0 Maintenance. International Conference on Virtual Reality and Augmented Reality, 170–180.

When consulting a P&ID an operator does not have to handle other tools, thus s/he can easily use other devices such as a tablet or a smartphone, hence, we believe that this is an application scenario in which HHDs can be a feasible solution.

As already stated, one of the biggest impacts of the fourth industrial revolution on industrial companies is the shift from mass production to mass customization of their products. This process will involve a revision of the production chain management models as well as the use of innovative technologies. The new production lines then will be suitable for rapid change in their configuration to satisfy customer requirements. In these smart factories, plants will be even more complex, and their configuration will change over the time (e.g. in case of maintenance, plant upgrade, and so on). It is important to provide operators, working on the plant, with all the updated information about it. For example, designers that are planning a new production need to know the layout and the interconnections between the components of the plant, maintenance operators need information about the history of maintenance of a machine, new operators need to understand how the plant is made, and so on. Currently, this information is stored in the P&ID (Piping and Instrumentation Diagram or Process and Instrumentation Diagram) and in the documentation stored in the factory archives. P&ID is a drawing showing the interconnections between the equipment of a process, the system piping and the instrumentation used to control the process itself.

According to Weber [197] ,P&ID are widely used in the planning and maintenance processes in the industry. Common tools for the creation of these graphical plans for hydraulic systems are (amongst others) Autodesk AutoCAD, Microsoft Visio, and Lucidchart. However, the representation through the P&ID of a plant is not the best visualization method, especially for complex plants. Indeed, a deep knowledge of the plant is necessary to quickly understand the function of each machine. The P&ID does not contain additional information regarding machinery, such as the description of the machine's functionality or the maintenance history. It also requires constant updating because of system modifications. Many companies use P&ID in paper form, for which the recognition of the various components and their functions is often tied to the know-how of the technicians working in the company.

5.1. Related Work

In the literature, several attempts of introducing a data-driven approach in industrial procedures were made, also exploiting AR. For example, Mourtzis et al. [198] presented a condition-based preventive maintenance approach integrated into a machine monitor framework. The system gathers and processes data, related to the operation of machine tools and equipment, and calculates the expected remaining useful life of components. Then, the system provides notification to process operators and maintenance department in case of the failure events during production.

Pintzos et al. [199] proposed a framework for the use of AR goggles coupled with handheld devices to assist operators for manual assembly. In this framework, there is an application related to the monitoring of process indices, which were displayed on the AR goggles in the form of KPIs related to time, cost, quality, and energy values.

Segovia et al. [200] implemented a system that exploits AR to display KPIs gathered from measuring devices, in the corresponding of workstations inside an industrial plant. They tested the system in a machine shop department against two not-AR modalities. They report that AR provides a simplified way to access the process performance information of several workstations in a production line, then it is no longer necessary to visit each station one by one to consult their status.

Liu et al. [201] presented a new generation of the machine tool with an AR-enabled process monitoring, thus integrating the AR technology with real-time process data from the CNC controller and various sensors to provide users with an intuitive perception of the machining processes. Furthermore, prognostic and health information can also be rendered on the related components to indicate the health status and remaining life so that proactive maintenance can be realized during the machining process.

Only a few of the systems presented in these and other similar works were tested in a real or simulated scenario. Most of them are just prototypes; then, it is difficult to consider all the issues in the implementation of such solutions, including human factors. For example, especially in small and medium-sized enterprises (SMEs), the operators are still accustomed to the knowledge-based approach, mainly based on drawings as the P&ID.

Furthermore, many companies use P&ID in paper form, for which the recognition of the various components and their functions is often tied to the know-how of the technicians working in the company. Other works have already been presented in the literature, to improve the comprehensibility of P&ID. Many specialists have tried to develop systems that automatically transform the P&ID from a paper to a digital form, including the automatic recognition of the component. Arroyo et al. [202] presented a method based on optical recognition and semantic analysis, which is capable of automatically converting legacy engineering documents, specifically P&ID, into object-oriented plant descriptions and ultimately into qualitative plant simulation models. Tan et al. [203] proposed a novel framework for automated recognition of components in a P&ID of raster form, based on image processing techniques to make a mathematical representation of the scanned image. They further extended this method to acquire also the connectivity among the components [204].

Considering state of the art, we then presented an AR application that allows the introduction of the data-based approach in a more gradual way within industrial plants, integrating it with the knowledge-based system already present in the enterprise and mainly based on technical drawings as the P&IDs. Furthermore, we tested this application through a user study.

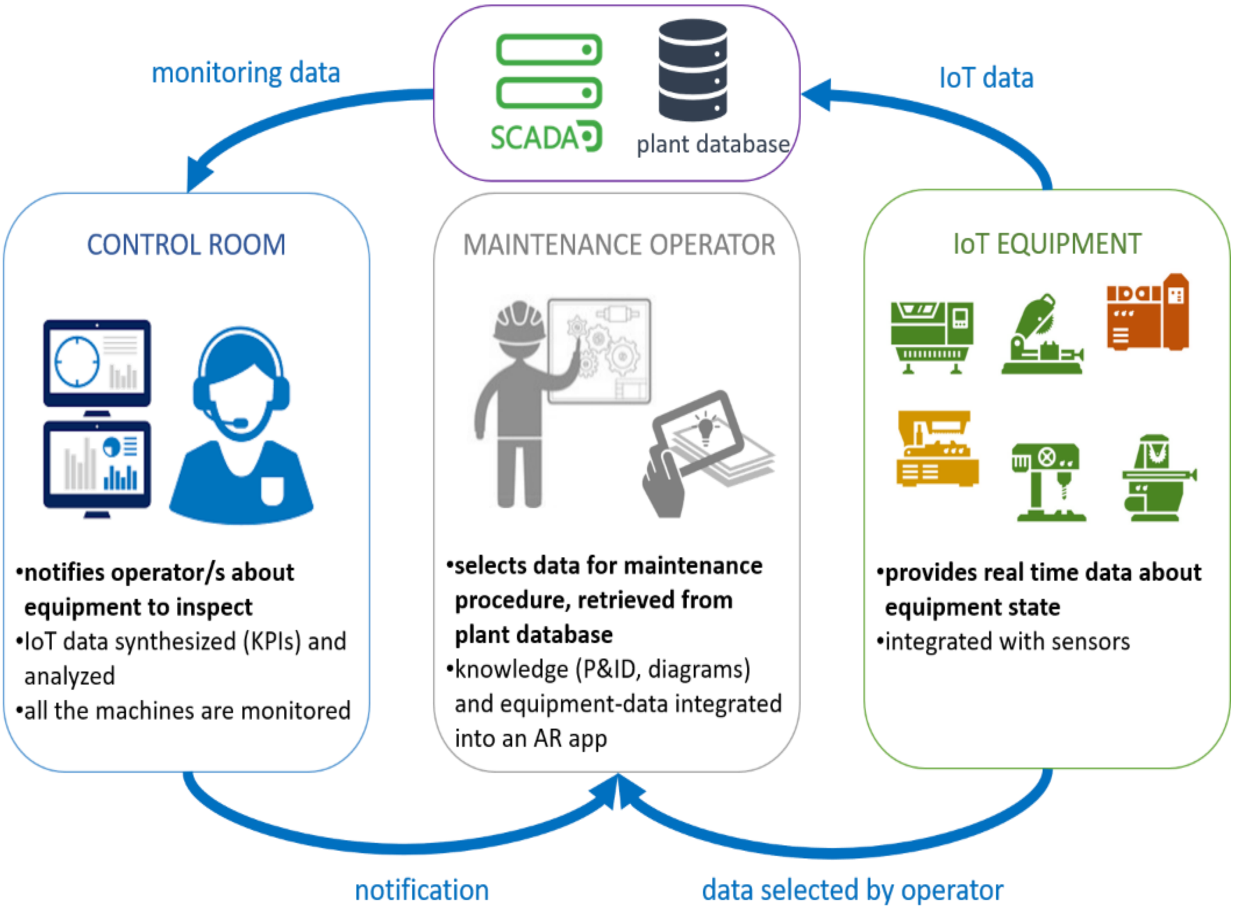


Fig. 34 Description of information flow for maintenance task according to our approach.

5.2. Design Approach

The application developed in this work supports the operator in the maintenance of a manufacturing plant using AR, providing information about the equipment to inspect directly on P&ID drawings.

In the system that we introduce (Fig. 34), equipment data are stored in the plant database and analyzed by a control room. It notifies the operator/s about the equipment to inspect communicating its code. Then, the maintenance operator searches the equipment to inspect on the P&ID. At this point, to accomplish the maintenance procedure, he/she needs other information about the component and/or the process. This information could be either plate technical data or real-time data coming from the process database, either numeric or in the form of other graphical visual assets. The presented application allows the operator to access all this information augmenting the P&ID drawing through these data.

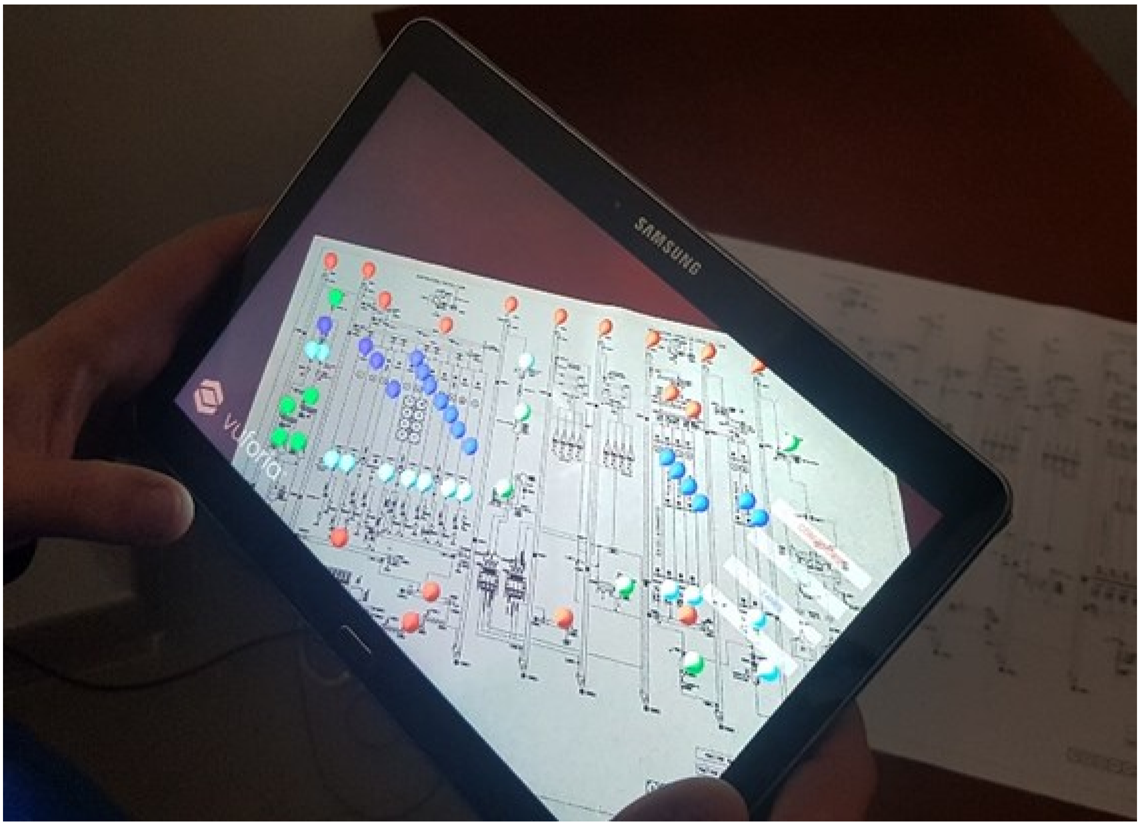


Fig. 35 The interface of AR application for P&ID augmentation.

In a first prototype of the AR application (Fig. 35), virtual hotspots are displayed in correspondence of plant elements on the P&ID; the hotspots could be of assorted colors to indicate different elements: e.g., pumps, conveyors, filters, and so on. Users can filter the hotspots displayed at the same time, grouped either by category (e.g., all the pumps, all the conveyors, and so on) or by subsections of the plant. Though operators are familiar with P&ID reading, this filtering utility facilitates the location on the P&ID of plant element to be analyzed, especially in case of layout modifications.

When users tap on the virtual hotspot on a plant element (Fig. 36), that hotspot gets bigger, whereas the others get smaller and become not selectable, and the name of the plant component is displayed for a check. A menu appears on the screen with three selectable buttons. These 3D buttons (pie menu) are registered on the trackable as a generic virtual element, and when the user clicks a second time on the hotspot, the menu disappears.

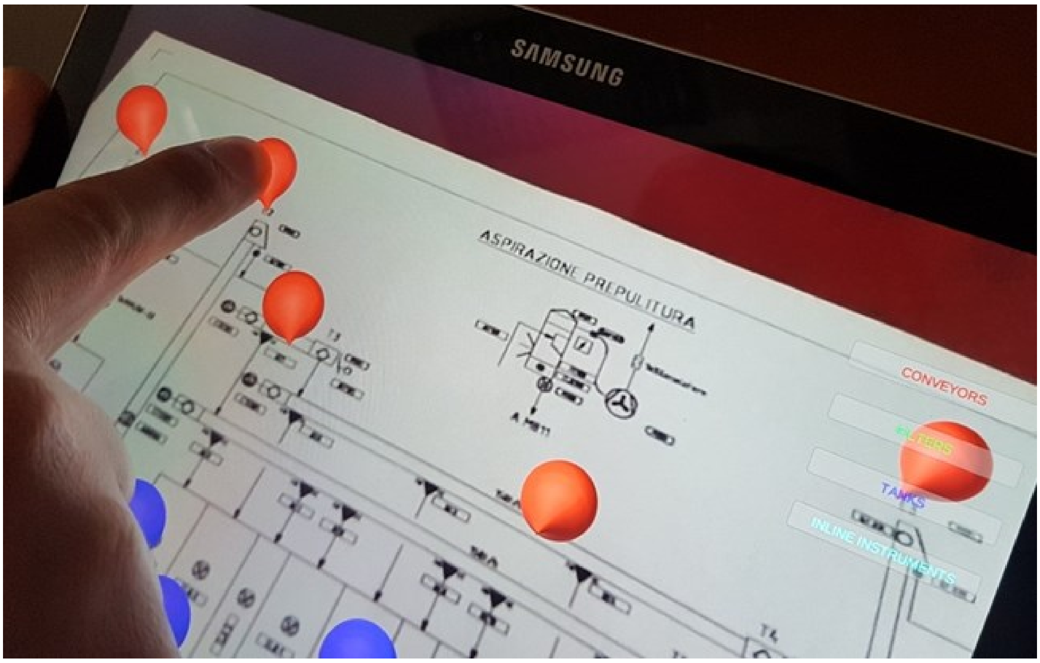


Fig. 36 User tapping on the hotspot to visualize the menu to access technical information.

A first button opens a technical chart of the component with all the information retrieved from the factory database where all the information associated with the plant components is stored. This information could be plate data (e.g., model number, supplier, efficiency, and so on), history data (for example, about maintenance and modifications), real-time data coming from process database.

A second button opens a navigable 3D CAD model of the selected component where, based on the available information, areas of the machine that require an inspection (e.g., bearings in a transmission shaft) can be highlighted.

A third button opens a 360-degree image of the component and its surroundings in the real plant. In this way, operators can rapidly associate the drawing to a physical location within the plant and know-how the component is connected to the rest of the plant.

The application was designed using Unity 3D and Vuforia for the AR behavior. We used the image-based tracking using the digital version of the drawing as trackable ; an important remark is that all the lines in the drawing should be black to achieve the highest tracking quality. Black lines on white sheets are mostly used in technical drawings, according to the drawing standards (UNI EN ISO 128-20:2002), however for P&ID other line colors are often used because many lines may overlap and also to distinguish the fluids flowing. From “AutoCAD plant 3D” we exported a datasheet of the (X, Y) coordinates of the plant components and they were used for the positioning of the virtual hotspots in Unity 3D. In AutoCAD each block represents a machine, the machines are divided by category to filter more effectively, and each category is also assigned a different color. In Unity 3D, a C# script reads the .txt file generated by AutoCAD with information about the location, color, tag, name. Then, in the Unity 3D scene, a copy of the hotspot is created for each machine (Fig. 37) with all the previous information automatically assigned. Then, we developed a second C# script to filter the visualization of the components displayed at the same time. The behavior of the pie menu is managed linking to the buttons a new Unity 3D scene with the 3D CAD model and the 360-degree image, respectively.

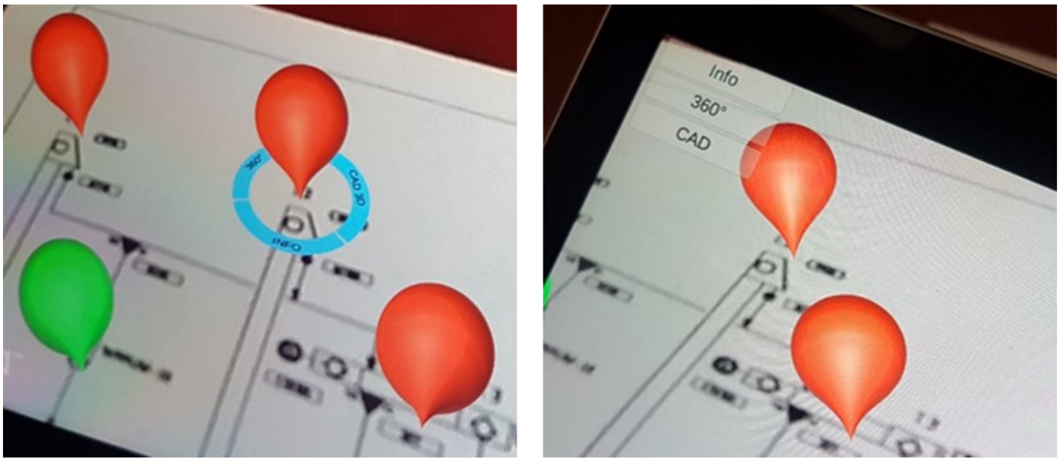


Fig. 37 Comparison of the hotspot menu layout: 3D on the left and 2D on the right.

For the technical chart, the link opens a 2D window (Fig. 38) that was designed and added to the canvas. For the information filling in the chart, we took it from an SQLite database automatically generated from AutoCAD Plant 3D. The information can be added either in AutoCAD Plant 3D or in the database since they are synchronized.

NOME Cassettone 2
DESCRIZIONE Serbatoio
PIANO 3
CODICE ED415

Fig. 38 Visualization of additional technical information through a pie menu: a technical chart with information retrieved from a database, a navigable 3D CAD model, and a 360-degree image of a plant section.

5.3. User Evaluation

We designed a user study to answer our research questions. We implemented a prototype of our application for the maintenance of a flour milling plant. During the experiment, users were asked to retrieve information about plant components on the P&ID. The P&ID was that of the cleaning section of the milling plant.

Components on the P&ID were indicated by the experimenter. Then, users had to search and communicate aloud the following information about the component: equipment type, the floor where it is located. We limited to information already present in the paper documents, besides the specific information does not affect the results. The task was repeated for five different components, and the overall time between the indication of the first component and the communication of the information for the fifth component was measured. An experimenter supervised each test and checked for errors in real-time. Users accomplished the task in three modalities:

- Paper: information about the component is retrieved from tables on paper sheets like those commonly used in actual practices.

- Smartphone: information about the component is retrieved from the AR application we developed running on a smartphone OnePlus 3 (screen size 5.5”).
- Tablet: information about the component are retrieved from the AR application we developed running on a tablet SAMSUNG Galaxy Note 10.1 (screen size 10.1”).

At the beginning of the experiment, we formulated the following hypotheses for the task of information retrieving for plant equipment:

(H1) AR application will significantly reduce the amount of time compared to paper documentation;

(H2) AR application will significantly reduce errors compared to paper documentation;

(H3) AR application will significantly improve usability compared to paper documentation;

(H4) performance in terms of time, error, and usability will be better for a tablet than for a smartphone.

A total of 39 voluntary participants (9 females) were recruited among engineering students at Polytechnic University of Bari. The average age was 24.2 (min 22, max 29, SD = 1.92). We interviewed the subjects about their frequency of usage of AR applications: 13 never, 15 rarely, 8 sometimes, 3 often, and none always used AR applications. Among users who had used at least once AR applications, the fields of use were video gaming (9), social network (8), cultural heritage (4), DIY (3), retail (2). Conversely, users had great familiarity with paper manuals/drawings: 2 sometimes, 3 often, 34 always used them. Users had no experience with plant maintenance tasks, but we designed a very basic experiment whose results are not affected by user experience and motivation.
A total of 39 voluntary participants (9 females) were recruited among engineering students at Polytechnic University of Bari. The average age was 24.2 (min 22, max 29, SD = 1.92).

We interviewed the subjects about their frequency of usage of AR applications: 13 never, 15 rarely, 8 sometimes, 3 often, and none always used AR applications. Among users who had used at least once AR applications, the fields of use were video gaming (9), social network (8), cultural heritage (4), DIY (3), retail (2). Conversely, users had great familiarity with paper manuals/drawings: 2 sometimes, 3 often, 34 always used them. Users had no experience with plant maintenance tasks, but we designed a very basic experiment whose results are not affected by user experience and motivation.

We used a Latin square design of the experiment. Then, we had thirteen participants performing the task in the sequence "Paper-Smartphone-Tablet," thirteen in the sequence "Smartphone-Tablet-Paper," and thirteen in the sequence "Tablet-Paper-Smartphone." They were told to complete each task as quickly and as accurately as possible. Each participant was allowed to familiarize with the three modalities for 10 minutes before the test. This training phase helped the participants to get accustomed to the AR user interface. At the end of the training phase, an experimenter checked that the participant was able to use the application easily. After completing the test, users were asked to respond to a SUS (System Usability Scale) questionnaire, to evaluate the usability of the three modalities.

5.4. **Results**

Our purpose was to evaluate the main effects of the execution modalities on user performance. Thus, we collected data into three samples, one for each modality. We had three types of data: completion time, error rate, and the SUS score.

To make statistical inferences, we started to enquire whether the completion time sample followed a normal distribution. We used the Shapiro-Wilk normality test, AS R94 algorithm, on all samples. All the original samples did not follow a normal distribution; thus, we applied the Box-Cox transformation with $\alpha=-0.9241$. Transformed samples positively passed normality (Paper: $W(39)=0.968$, $p=0.324$; Smartphone: $W(39)=0.964$, $p=0.241$; Tablet: $W(39)=0.971$, $p=0.411$) and homoscedasticity test ($F(2, 114)=0.275$, $p=0.760$). Then, we used ANOVA to compare the samples. We found a statistically significant difference between the three samples ($F(2, 114)=63.974$, $p<0.001$). Tukey's posthoc test revealed that users performed significantly better with "smartphone" than "paper" ($p<0.001$) and with "tablet" than "paper" ($p<0.001$), whereas there was not a statistically significant difference between "smartphone" and "tablet" ($p=0.997$) modalities. Mean completion times (Fig. 39) are: 118.2 seconds for "paper," 66.5 seconds for "tablet," and 65.0 seconds for "smartphone." These results allow us to confirm hypothesis H1 and to reject hypothesis H4.

We used the following error rate definition:

$$ER\%=(n.errors)/(n.targets)\cdot 100$$

The *"n.errors"* is the sum of all the participants' errors observed for each task. The *"n.targets"* is the maximum number of errors that a user could make for each task (5), multiplied by the number of participants that performed the experiment (39). We used the method of "nx2 contingency tables" to make a statistical inference.

We did not find a significant difference between error rates of the three samples ($\chi^2(2)=3.866$, $p=0.145$). Error rates are: 3.08% for “paper”, 1.54% for “tablet”, and 0.51% for “smartphone”. These results allow us to reject both hypotheses H2 and H4. Also, for SUS scores, we first checked the samples for normality. Two out of three of the original samples did not follow a normal distribution. Thus, we applied the Box-Cox transformation with $\alpha=3.0378$. However, the “paper” sample did not follow normal distribution also with the transformation. Then, we used the Kruskal-Wallis test for the sample comparison. We found a statistically significant difference between the three samples ($\chi^2(2)=57.626$, $p<0.001$). Pairwise comparisons revealed that usability was significantly higher with “smartphone” than “paper” ($T=-48.577$, $p<0.001$), as well as with “tablet” than “paper” ($T=-52.077$, $p<0.001$), whereas there was not a statistically significant difference between “smartphone” and “tablet” ($T=-3.500$ $p=1.000$) modalities. Mean SUS scores are (Fig. 3): 55.4 for “paper,” 84.6 for “smartphone,” and 86.9 for “tablet.” These results allow us to confirm hypothesis H3 and to reject hypothesis H4.

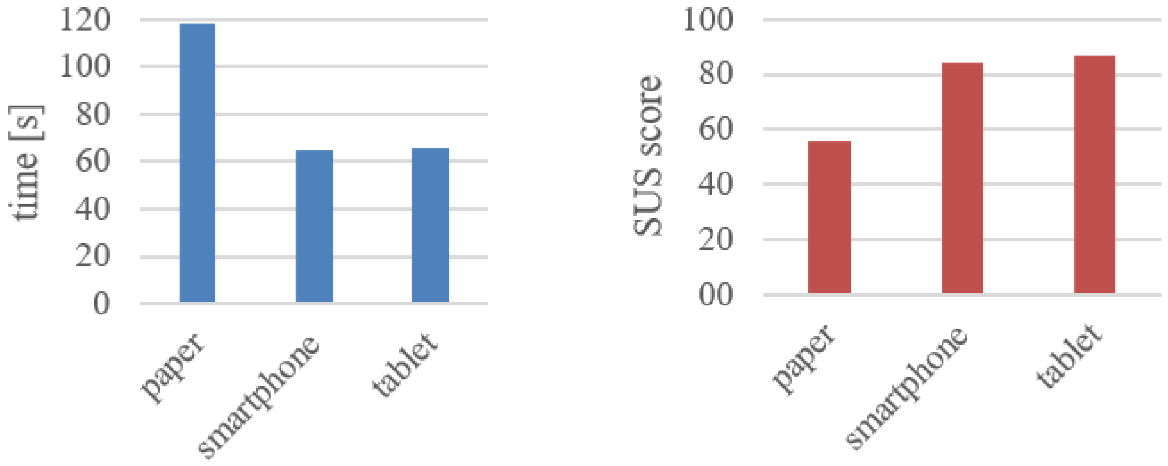


Fig. 39 Results about mean time (left) and SUS score (right) of the user study for the three execution modalities.

5.5. Discussion of Results

We developed an AR application that augments a P&ID drawing of a plant, thus allowing operators to retrieve useful information for the maintenance procedure, as the location of equipment in the plant.

We effectively tested the application in the scenario of a milling plant through a user study. Considering the results of the user study, we found that AR is effective in the retrieval information task in term of task time reduction. This result confirms what was found in the literature in other industrial scenarios [205]–[207]. However, in terms of error rate, we did not detect any statistically significant difference between the use of AR and paper documentation. This could be due to low task difficulty.

The SUS test reveals that users prefer to use the AR application rather than paper documentation, although they are more accustomed to paper manuals/drawings than to AR. This result is mainly due to the minimalist, but effective design of the interface designed for this application, compliant to our vision of a gradual introduction of new approaches in industrial practices.

An interesting result, for the AR modality, is that the use of handheld devices with different screen sizes (smartphone and tablet) does not affect user performance. In a smaller screen, the density of virtual elements simultaneously displayed in the interface is higher. Then, the distance between two hotspots in our application is lower in the smartphone, thus increasing the possibility to interact with the wrong hotspot. However, we noted that the user naturally tended to bring the smartphone closer to the drawing after they understood which hotspot interact with. On the other side, having a device with a smaller screen implies an easier and more rapid interaction with touch, which can also be done with one hand.

An innovative aspect of the proposed solution is the automatic update of the virtual hotspot location on the P&ID when there is a layout modification in the plant. In this way, using our application, operators can accomplish their maintenance tasks with low mnemonic effort even in case of frequent layout modifications, a situation even more frequent in the Industry 4.0 context. Furthermore, external operators, that do not know the plant layout and processes can be employed. With this tool, technicians can easily understand the components and connections in the plants even if they do not know the coding of the symbols used in the P&ID. However, this tool does not help operators in support of decisions, since it does not provide further information, for example, for the planning of maintenance procedures. Then, a future step of this research will be the integration of other features in the framework, as the identification of the equipment to inspect on the drawing and the displaying of selected KPIs directly superimposed on the equipment.

In the last chapter, we investigate the utility of a context-aware information manager as applied in an industrial AR setting of the Mill 4.0.

Chapter 6. AR Context-Aware Technical Documentation Manager for Mill 4.0

The evolution of computer-based user interfaces has seen many innovations over the years especially in AR devices and applications. Of particular note is the nature or design of information presented; notably both the content presented and the form in which the content takes. Early command-based ASCII interfaces required all users to memorize commands to elicit text-based system responses. 2D graphical user interface (GUI) windowing systems afforded multimedia presentation of content and some flexibility for interface designers in terms of spatial arrangement. However, it was advances in both e-learning and e-training applications, as well as, web-based technology that ushered in an era of dynamic user interfaces designed to sense aspects of the current context (e.g., a user's recent search history) to dynamically present content (e.g., web-based recommendation system for related products or targeted advertisements).

Moving forward, we should expect the traditional "one size fits all" design approach to AR interface design (e.g., information content and presentation style) to become replaced by AI-driven active, real-time and context-aware user interfaces that not only customize the information content but how that information is displayed. Such active user interface systems should leverage, for example, deep and longitudinal understanding of specific users, their goals and tasks in the moment, users' past experiences with and implicit preferences in related tasks, as well as environmental and hardware constraints in which they use the interfaces.

By developing practical industrial case studies, we faced issues in managing the presentation of technical information. Therefore, in this chapter[5], we explore the utility of a context-aware information manager as applied in an industrial AR setting of the Mill 4.0. Specifically, we present CATIM (Context-Aware Technical Information Manager), a system capable of

---

[5] Part of the results of the studies described in this chapter were published in the following paper: Gattullo, M, Evangelista A., Manghisi, V. M, Uva, A. E., Fiorentino, M., Boccaccio, Ruta, M., Gabbard J.L. (2020). Towards Next Generation Technical Documentation in Augmented Reality Using a Context-Aware Information Manager. Applied Sciences MDPI, vol.10 n.3 780.

rendering technical documentation via an active AR interface, dynamically guided by the context.

In literature, we have found few studies examining context-aware retrieval systems specifically focused on technical information presentation in AR. Of similar approaches found, most do not specifically consider a large set of context features such as user characteristics, environment, and hardware. Therefore, a contribution of this work includes a technical information manager for AR user interfaces capable of adapting to a number of contextual dimensions and therefore usable in a wide array of operating conditions.

Firstly, operators can be different one from the other. They can have different levels of expertise and experience. As to experience level, we can distinguish from novice to expert operators according to the knowledge acquired performing technical procedures. However, a same operator could have a greater expertise on a particular machine/product than on others. Experience can regard different skills as assembling skills, using the tools, problem solving, and so on. Thus, some operators may want to read the explanation of each step, while others may understand everything by just looking at an image of the procedure. Operators could have also different needs when consulting a technical manual given a certain task, someone may want to check a single step, others may have to follow the entire guide step-by-step. Younger people are digital natives [208], [209] and thus more oriented towards innovative displays, whereas older people would be more attached to traditional media. Finally, people speak different languages and come from different cultures [210], then also technical documentation is affected by these differences. The domain of technical documentation covers several application environments. This might allow the use of some specific user interfaces for conveying information while making impossible or dangerous to use some others. For example, some application environments may not require great attention to the real world, while others may be critical or dangerous tasks, allowing attention loss on reality for just a few seconds [211].

As a result, the increasing number of technical documentations to produce, the variety of ways to convey information, the differences among people, and the variable environmental conditions, make sure that the authoring and the management of technical documentation becomes an issue. Many works on adaptive AR interfaces propose algorithms to determine optimal text styles (e.g., text color and drawing style, position of labeling), based on the background of the environment [86], [212], [213]. However, these works do not consider dynamically altering the information content or other contextual elements.

The management of large informative systems is a problem which has been broadly investigated in many fields, for example in information retrieval by research engines. Advanced context-aware information retrieval systems have shown excellent results in the e-learning and e-training contexts [214], [215]. However, to our best knowledge, the results from these studies often ignore the 'people' factor. The user must manually search for the information they are looking for, using some research keys. This requires previous knowledge in the domain that they may not have. Moreover, of similar approaches found in the literature [216]–[220], most do not specifically consider a large set of context features. Therefore, a contribution of this work includes a technical information manager for AR user interfaces capable of adapting to a number of contextual dimensions and therefore usable in a wide array of operating conditions.

This work draws motivation from our previous work in industrial AR-based maintenance. By developing practical industrial case studies, we faced issues in managing the presentation of technical information. Therefore, in this work, we implemented a system called CATIM (Context-Aware Technical Information Manager) that acquires data about the context (operator, activity, environment), and, based on these data, proposes documentation tailored to the current operating context. We made also a first evaluation of CATIM in a real industrial case study.

In Section 2, we present related work. In Section 3, we describe our approach. In Section 4, we explain the architecture and the implementation of CATIM. In Section 5, we report the application of CATIM to the case study. In Section 6, we present the results of this application and their discussion. In the final section, we provide conclusions and future work.

6.1. Related work

In literature, there are many works that quantify the effectiveness of AR for visually presenting technical information and manuals as measured by reduced time and operator error in the fulfillment of procedural task (e.g., [57], [133], [221]).

Beyond simply presenting technical information via fixed AR user interface designs, other researchers have looked to increase the utility of AR interfaces by incorporating context-aware features into AR applications. The context can condition the choice of the information content, the style of this content, or both.

For example, Oh et al. [216] combined context awareness and mobile augmented reality, proposing CAMAR (Context-Aware Mobile Augmented Reality). CAMAR customizes the content to be preferable to a user according to his/her profile, and to share augmented objects with other mobile users selectively in a customized way.

Grubert et al. [218] present a state-of-the-art context-aware AR system that considers the effect of context both on the content and the presentation style. They introduced the concept of pervasive augmented reality as a continuous, context-aware augmented reality experience. A goal of this work was to build an AR interface that is actually context-controlled, moving away from the single purpose AR application towards a multipurpose pervasive AR experience. However, their approach is limited to: (i) presenting the concept of pervasive AR; (ii) developing a taxonomy for it; (iii) providing a comprehensive overview of existing AR systems towards their vision of pervasive AR; and; (iv) identifying opportunities for future research. Our work can further this pervasive AR vision by providing a context-aware AR system that adapts well in many possible situations that an operator may encounter in industrial applications.

Ruta et al. [222] present a software system to assist in the discovery of points of interest for tourists in AR and their description in a way that can match users' interests. Even if the scope of this work is different from ours, the approach is similar in spirit: the automatic choice of the information to display and a customized way of displaying it, both based on the current usage context.

Hervás et al. [219] define mechanisms for the management of contextual information, reasoning techniques, and adaptable user interfaces to support augmented reality services that provide functionality to make decisions about what available information should be offered and how. The variables taken into account by their system are too abstract in terms of possible applications and user profiling. Furthermore, they do not cover maintenance/assembly tasks.

The previous works discussed thus far are not focused on the application of context-aware interfaces to industrial AR. Akbarinasaji and Homayounvala [223], present an optimized context-aware AR-based framework to assist technicians conducting maintenance tasks. The proposed framework makes use of collected raw context data and performs reasoning on them to obtain new inferred data and to provide adaptive behavior using an ontology.

Flatt et al. [224] present a system to display information in AR in an industrial context. Their approach implements a general-purpose application capable of applying textual 'sticky notes' to real objects, describing them with a semantic notation to be retrieved later. This work is more oriented to dynamic authoring and annotation rather than dynamic management of user interface information and presentation styles.

In many related previous works, there is a lack of focus on the field of maintenance and even in these cases just a few user interface assets are used (e.g., text, signs, and symbols). Thus, we applied the lessons learned in these previous studies about the use of AR in an industrial domain, to propose an appropriate behavior of CATIM. We considered the most relevant factors influencing the design of an AR interface in an industrial domain, as well as a wider range of technical information assets with a specific semantic description on when to use them.

Zhu et al. [220] present an authorable context-aware AR system (ACARS) using a specialized context description. They describe the maintenance procedure, the tools and the devices involved, as well as more synthetic information about users and the working environment. The context-aware system developed captures some parameters to select a set of information and a level of detail at which the information should be rendered. Although the system seems very interesting for our goals, their target is on-site authoring capability to assist maintenance technicians.

6.2. Materials and Methods

Our approach, whose functional scheme is depicted in Fig. 40, aims to present the operator with the ‘best’ technical assets available for the context. A technical asset is an atomic piece of technical information conveyed in a specific modality. Technical assets are usually visual cues such as CAD models, video, text, images, icons, graphs, and so on. The technical assets can be static but also associated to dynamic and time-dependent information. It is worth noting that, in our definition, the same technical information can be mapped to different assets sharing the same content but with different media and interface presentation style (e.g., short text, long text, animated text, video, audio). Thus, the choice of the optimal technical asset for the same technical information is paramount.

For CATIM, we assume that the context in which to perform a task can be known. For example, the system could infer the activity to be performed by automatically using state sensing, IoT or by user selection. CATIM could know the operator technical, physical and cognitive skills, as well as interface preferences by, for example, user profiling and wearable sensors. User profiling is currently carried out through a preliminary questionnaire provided to the operator. Lastly, the system could sense the environment using sensor suites and computer vision to identify available tools, lighting condition, available AR devices, and so forth.

Using our proposed approach, upon operator initiation of a task procedure, CATIM browses the technical information database to find the technical assets which best match the context and presents them to the operator via an AR user interface. The information search is based on the context description rather than having the user selecting the information needed. The information associated with each step of the procedure can be conveyed alternatively using different technical assets (e.g., text, icon, video, audio). Each asset (as used in each step of a procedure) can be linked to a particular state of the activity, of a process, of a product. Therefore, a procedure can be presented at runtime to the operator as a sequence of best context matching technical assets. Consequently, the presentation can be dynamically adapted to an operator's learning curve, as the operator can be continuously profiled by the acquired data (e.g., number of presentations of the same asset and task time for a repetitive procedure).

In the following sub-sections, we provide further details on each component of CATIM.

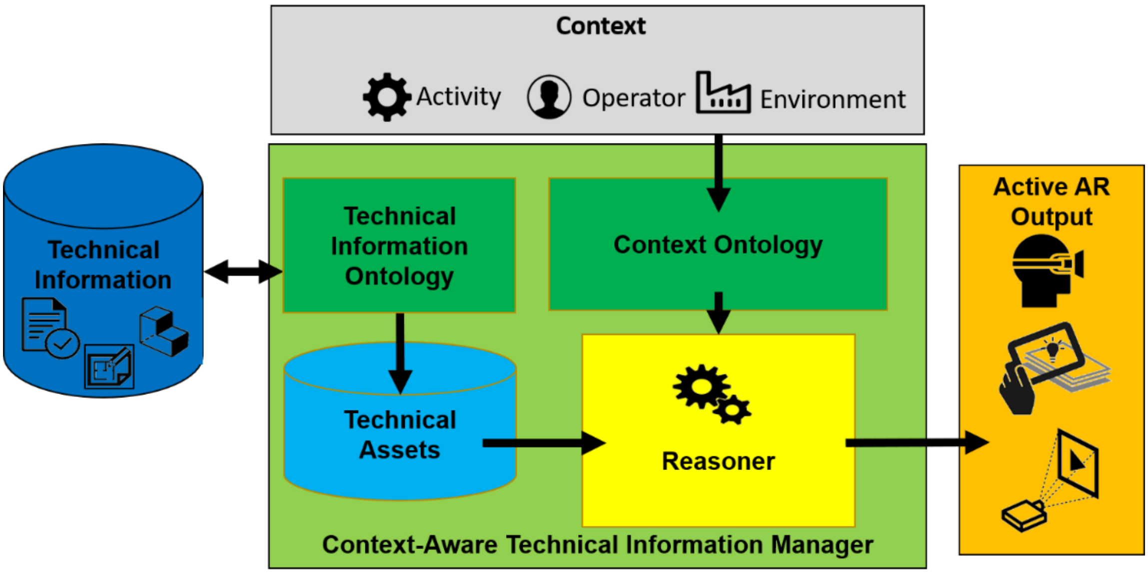


Fig. 40 CATIM Functional scheme: the Context-Aware Technical Information Manager dynamically maps the context and provide user with technical information through the best available technical assets into an active AR output.

6.2.1. Technical Information

Most of the technical information associated with a product or machine is stored in the form of technical documentation (i.e., manuals, technical drawings, specifications, standards, common practices). This technical documentation is increasingly composed of assets available in various digital formats. In these cases, CATIM can help identify specific assets (from a large set of possible assets) that are well-suited for the specific context and provide an alternative form if needed.

6.2.2. Context

Context may include any information that is relevant to CATIM to provide user with the best technical assets. Among all the dimensions generally used to define and describe the context, we consider only the following three to be representative of typical industrial AR settings.

6.2.3. **Activity**

The activity (i.e., a specific routine of definite steps to be performed on an equipment, as defined in [223]) is crucial for identifying the right technical information to present. The activity can be tracked in the simplest way by user selection (e.g., using a menu, by voice commands) or tracking automatically the state of the product, of a process or procedure (e.g., using object tracking, IoT sensors, and more generally any data available in Industry 4.0 cyber-physical systems). The tracked activity completion (or object state) can trigger the presentation of information related to the next activity. Thus, the activity can have a strong influence in the choice of the technical assets and even of the preferred AR device among those available.

6.2.4. **Environment**

Industrial environments are generally complex and risky due to the presence of static and moveable products, components, machinery, consumables, and tools. They may present very different conditions in terms of location (indoors and outdoors), network or system constraints, illumination, temperature, dirt, smoke, noises, dust, etc. Most industrial environments are characterized by the presence of hazards that may compromise the safety of the workers. Industrial environments, therefore, must follow mandatory safety regulations and procedures and operators must wear personal security devices (e.g., helmets and gloves). Industrial conditions and safety devices may reduce users sensing and perceptual capabilities like hearing, vision, touch, etc. To assist operators in these dynamic settings, active AR user interfaces should cope with the environment and complementary safety devices worn by operators during duty time. AR devices' availability and capabilities (e.g., contrast ratio, luminance, color gamut) must further fit the environmental context. Thus, the context-aware AR application interface and interaction must be designed according to the environment in order to assist operators physical and cognitive capabilities (e.g., operators' visual attention) and to avoid risks. Industrial environments may also limit situated visualization capabilities (e.g., uneven light conditions, dirt, moving machinery, etc.). Products, components, machinery, consumables, and tools, (e.g., screwdrivers, wrenches, etc.) often belong to an environment and may be available or not to the operator. Industrial objects can be easily tracked nowadays with IoT technology and full environment data will likely be available in the near future.

It is important to note that the dimensions presented herein are exemplary of industrial AR setting but could be extended to include other dimensions such as social contexts (e.g., impacts of other team workers), transient physiology in users (e.g., fatigue, sensitivity, mental workload), and so forth. Furthermore, CATIM can support additional dimensions altogether that in turn could support context-aware AR interfaces in other application domains.

6.3. Context-Aware-Technical Information Manager

Technical information is mapped onto a database of technical assets using an ontology for technical information. The context is then dynamically mapped onto a context vector also using a context ontology to describe the application domain. This vector contains data about the activity, the operator, and the environment. It can also contain other elements as tools and key performance indicators that can influence the choice of technical assets. A reasoner, using recommender system technology, selects the best technical assets according to the context vector and presents them dynamically using an active AR interface to the user.

Our system implementation uses a Java http back-end and a front-end mobile application implemented with Unity 3D to manage the active AR output on the AR device (see Fig. 41).

The Java http back-end receives context information and reasons using the ontology on the currently loaded domain. Both the technical information ontology and the context ontology are handled by Protégé, a broadly used software for the assisted generation/customization of Web Ontology Language (OWL) ontologies [225]. The reasoner uses two non-standard reasoning algorithms. For the technical information recommendation (i.e., what information to present), a concept contraction/abduction reasoning algorithm is used. For the technical asset type selection (i.e., how to present the information), we use the concept covering algorithm implemented in Mini-ME [226], which tries to compute the best consistent coverage for the current context. The various asset type descriptions are associated to ‘rules’, predefined by the application designer, to try to cover (without contradictions) all the concepts that describe the current context. The concept covering rules are used by the reasoner to compute the distance between the assets and the context vector. The back-end replies to front-end requests with a list of compatible technical assets, ordered according the concept covering distance. This ranking suggests the technical assets more appropriate to the current context. There could be some context scenarios where CATIM is not able to display instructions. This is mainly due to safety issues. For example, if the operator must have free hands for safety reasons and only smartphone is available as device, CATIM will not provide instructions suggesting using other displaying output (e.g., a monitor or a paper-based support). In this way, CATIM is also able to prevent specific risks in industrial environments.

6.4. Active AR Output

The active AR output application, running on the AR device as front-end, acquires information sent by the back-end and presents the technical assets organizing them according to context information (context-dependent layout). User selection on the AR interface triggers a request to the backend for the analysis of the current context. Then, the frontend application, on the AR device, receives the ordered set of compatible technical assets. The active AR application shows just the first asset (i.e., the one with the shortest distance) is selected for visualization, but the user, through a button in the GUI or with voice command, can show the other assets in the set.

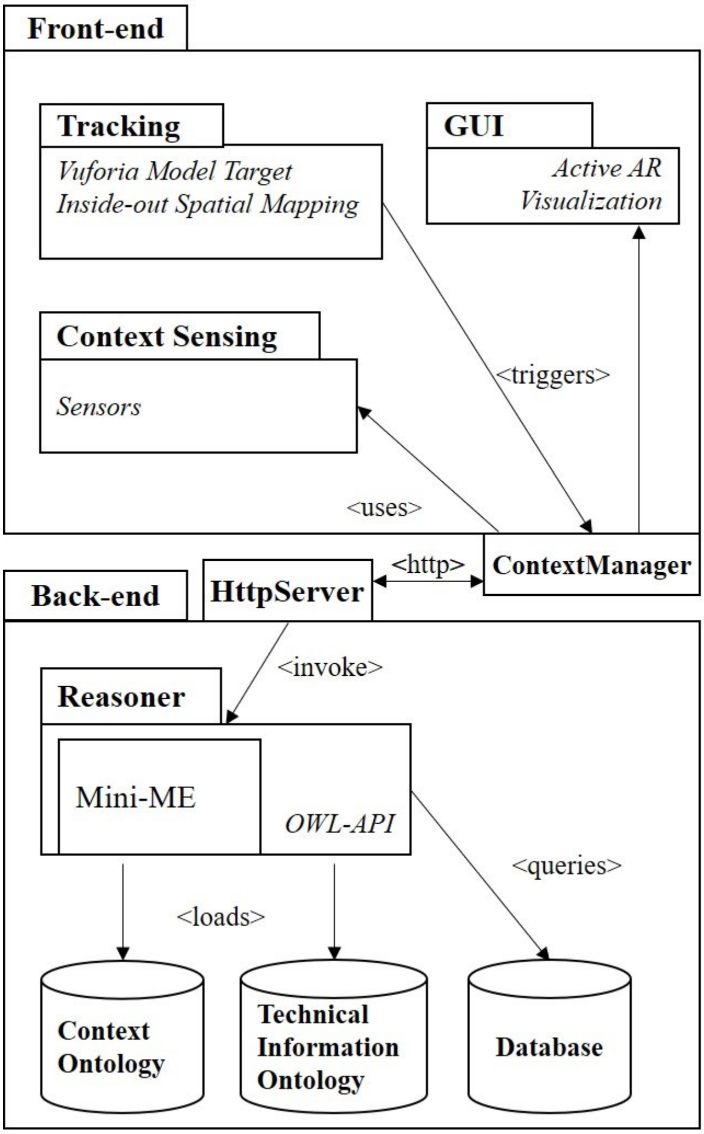


Fig. 41 System implementation consisting of a Java http back-end and a front-end mobile application to manage the active AR output.

The registration of virtual AR objects on the real world is made possible using the Vuforia Model Target Feature, which recognizes and tracks a physical object using a digital 3D model of the object. We developed this application both for Android mobile devices and for the Microsoft HoloLens. For HoloLens, we also used its inside-out spatial mapping for the positioning of the GUI in a fixed region of the surrounding space. We implemented a basic interface whose purpose is just to test the right behavior of CATIM. User selection is made by tapping on a virtual element (handheld device) or by using an air-tap (i.e., one of the standard gestures recognized by HoloLens).

6.5. Deployment of CATIM in an Industrial Case Study

In this first evaluation, we show how CATIM can be applied to a maintenance procedure for a f grain cleaning system component. Specifically, we examine how context-aware AR can assist in the inspection of an electrical motor that manages inspection and maintenance (see Fig. 42 and Fig. 43). Since this inspection is typically performed before the motor's installation.

To remove the fan protection cover, unscrew the three screws at the base of the protection cover and separate the cover from the motor body.

Fig. 42 Example of user interacting through (a) air-tap with the AR interface displayed on the HoloLens (AR interface added to the image in post-processing phase).

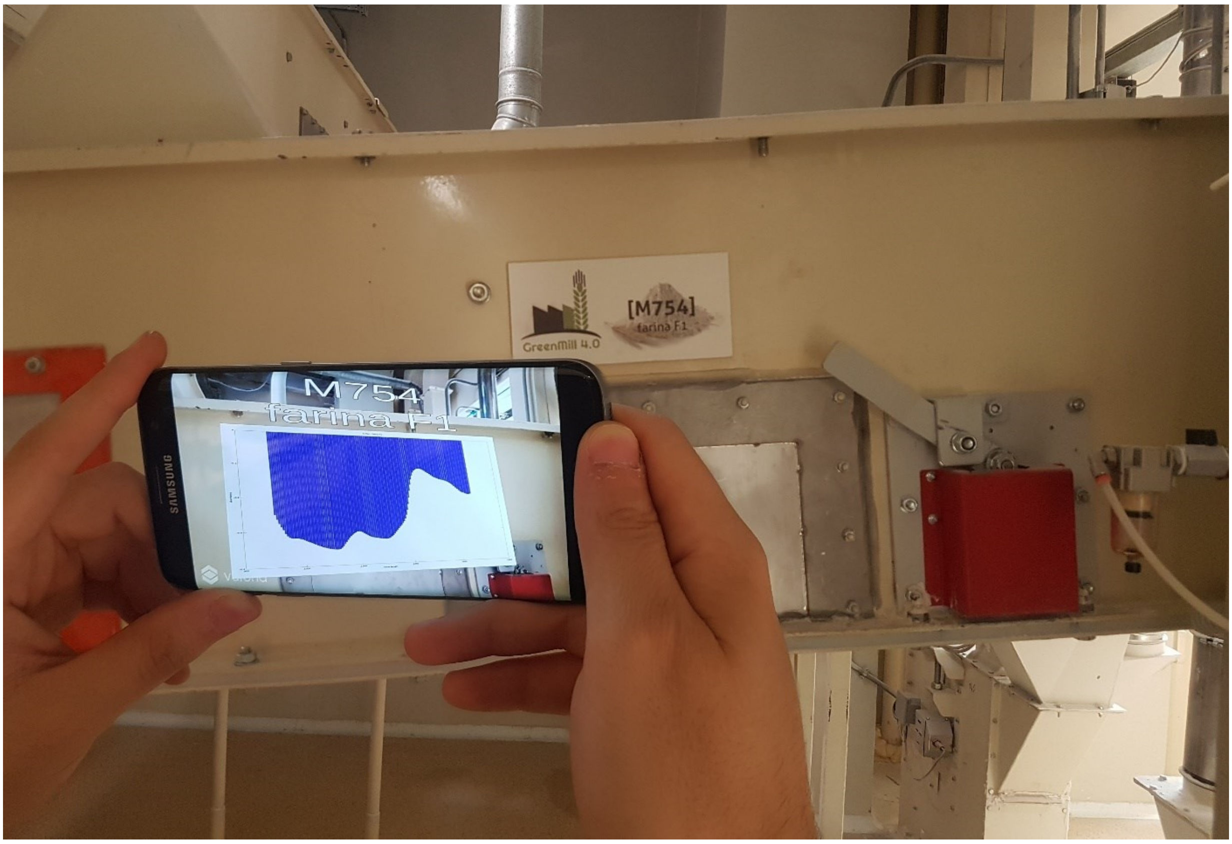


Fig. 43 Example of user interacting through touch on screen with the AR interface displayed on smartphone.

The operator's inspection instruction is representative of some of the most common tasks in the industrial field: part localization, manual and checking operations. We used the CAD model of the electric motor and the text instructions taken from the manufacturer's technical manual for the electric motor: "To remove the fan protection cover, unscrew the three screws at the base of the protection cover and separate the cover from the motor body.". The case study presented herein is limited to a single inspection instruction, thus the interaction between users and the AR application is not related to browsing different instructions, but to the request of additional visual assets respect to those proposed by CATIM. However, the system can support also lengthy procedures consisting of many inspection instructions, thus producing an interactive AR manual that can be browsed by operators.

The ontology architecture for the case study is designed specifically for the information contained in technical manuals and it is composed of three levels: upper ontology, lower ontology, and database as described in Fig. 44.

The PC used as the backend in the case study run an i7-6700HQ (2.60 GHz) with 16 GB RAM, with Windows 10 operating system. The AR visualization devices were:

- Microsoft HoloLens (2016);

- Samsung Galaxy S7 Edge (AnTuTu v7 [227] score: 158);
- Sony Xperia Z3 compact (AnTuTu v7 score: 59);
- Google LG Nexus 5 (AnTuTu v7 score: 57).

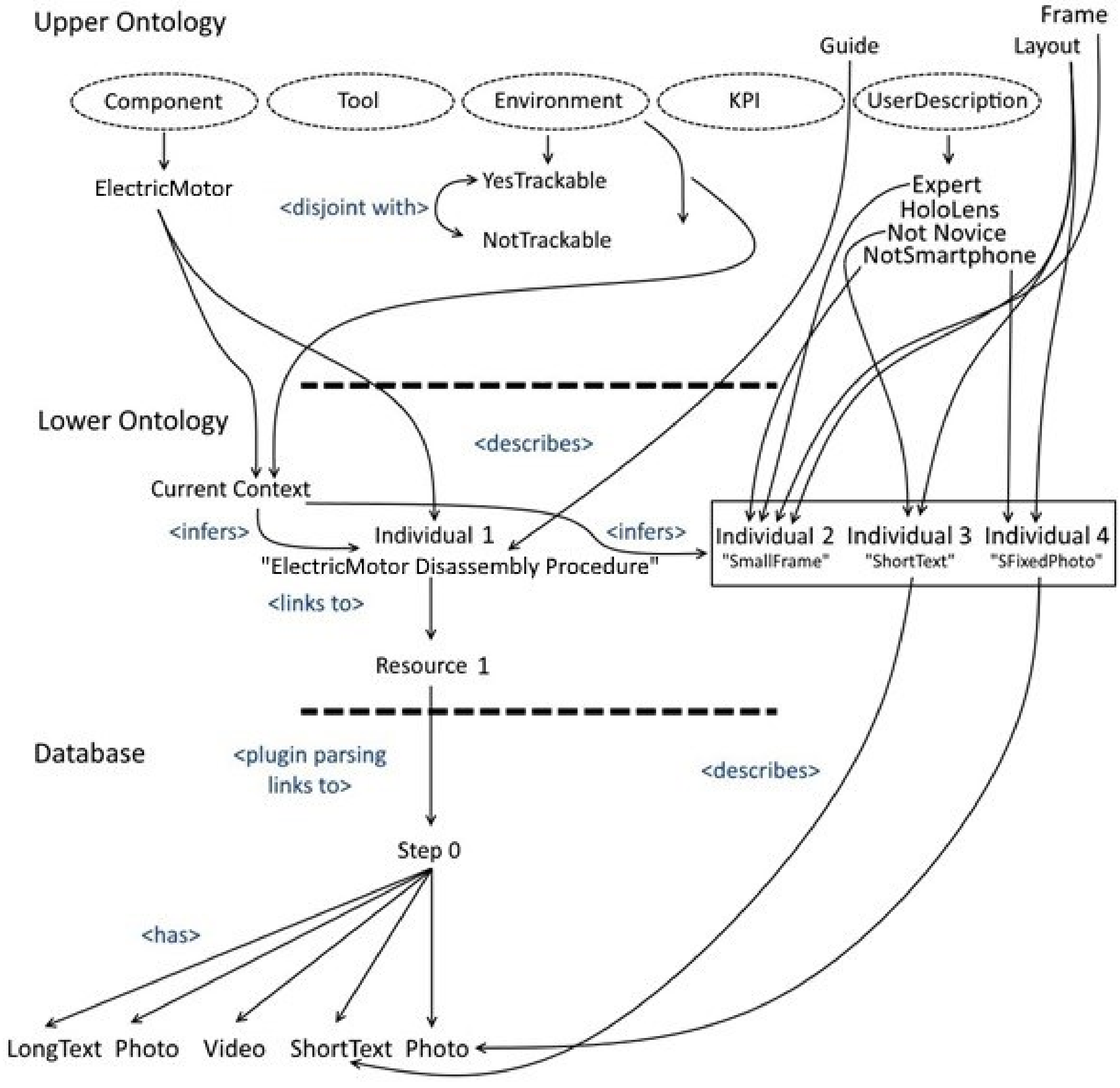


Fig. 44 Example of the ontology architecture used in the first evaluation of CATIM.

6.5.1. **Technical Assets**

We defined the technical asset types to be used in our case study and, starting from the available technical information, we generated the correspondent technical assets:

- Short text, taken verbatim from the real manual: “Remove the fan protective cover”.

- Long text, that details the instruction for novice users: “To remove the fan protection cover, unscrew the three screws at the base of the protection cover and separate the cover from the motor body.”.
- Short audio, that is the short text delivered by a speech synthesis program.
- Long audio, that is the long text delivered by a speech synthesis program.
- Annotated photograph, that is a picture of the motor with annotations useful to understand the tasks to accomplish (Fig. 45).
- Video tutorial, that is the recording of the operation previously accomplished by an operator (Fig. 46). As for the annotated photograph, the video can be either screen-fixed or world-fixed.
- Product model, that is the animation of the CAD model of a screwdriver indicating the position of the screws and the direction of unscrewing (Fig. 47).

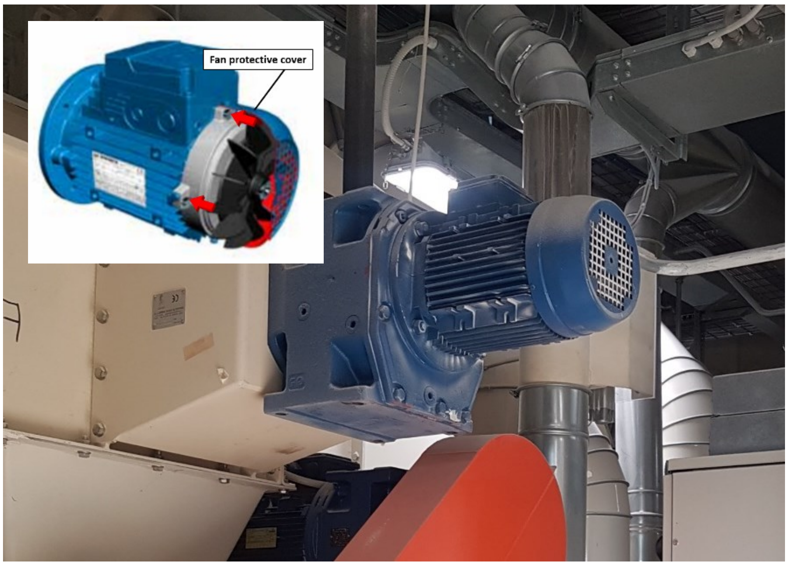


Fig. 45 Multimedia asset generated to convey the instruction: an annotated photo.

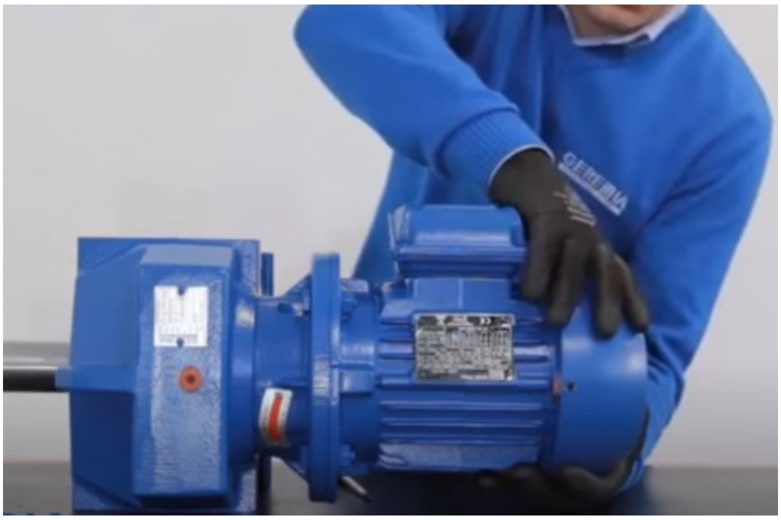


Fig. 46 Multimedia asset generated to convey the instruction: video tutorial shows the task performed by an operator.

Fig. 47 Multimedia asset generated to convey the instruction: an animated CAD models superimposed on electric motor.

Through AR devices, visual assets can be either directly superimposed on real-world referents (world-fixed) or fixed to a designated area within a display's field of view (screen-fixed). A photograph can be rendered at a fixed location on the GUI (i.e., screen-fixed) or at a specific location in the real world (i.e., world-fixed).

6.5.2. **Context Ontology: Activity, Operator, Environment**

For the context, we consider the activity as fixed (i.e., the chosen single instruction). For the operator, we consider the single attribute of user experience (values: novice and expert user). For the environment, we consider three attributes: (i) object trackability for situated visualization (values: trackable or not trackable), (ii) noise (values: noisy and acceptable), and (iii) AR device (values: HoloLens and smartphone). In this evaluation, we simulated that these values were automatically recognized by CATIM through sensors (noise), user profiling (experience, device), retrieval of object information from the database (trackability). Various combinations of these simulated values were manually forced in the context vector.

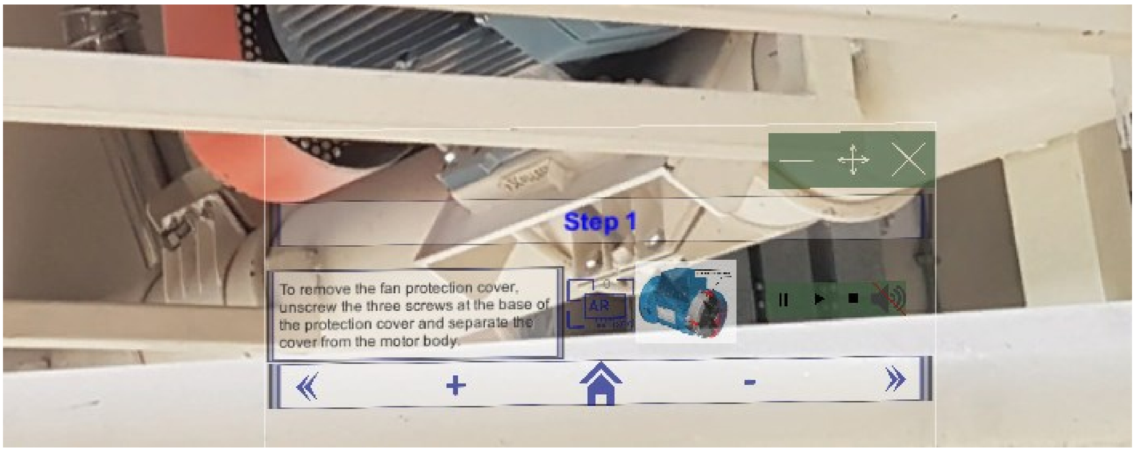
The concept covering rules, presented in Tab. 10, are defined once for the scope of the application to formalize the design choices. The following design choices were made together with the operators that constantly collaborate with us. For operator experience, we decided not to show to an expert operator detailed technical information assets such as long text/audio, world-fixed assets, and the video tutorial. We assume that an expert operator knows how to accomplish the task, whereas a novice operator could need more detailed instructions. As to device, with the HoloLens we decided not to show long text because of its limited field of view (FOV), while with the smartphone such screen-fixed content could occlude the real world. As to trackability, when the scene\objects are not trackable, we decided not to show world-fixed contents. This could be due either to the inadequacy of the target objects for the tracking method chosen or to external factors such as the forbiddance to put the optical marker on the scene. Finally, as to noise, we decided not to use audio in noisy environments.

Tab. 10 Concept covering rules: for every technical information assets, we listed the conditions where they are discarded, according to design choices to let the AR application work always in an optimal way.

		Operator				**Environment**			
Technical Asset Types		**Experience**		**Device**		**Trackability**		**Noise**	
		Expert	**Novice**	**HoloLens**	**Smartphone**	**Not Trackable**	**Trackable**	**Noisy**	**Acceptable**
Text	Long	*Discarded*		*Discarded*					
	Short		*Discarded*						
Annotated Photograph	W-fixed	*Discarded*				*Discarded*			
	S-fixed				*Discarded*				
Product model	W-fixed	*Discarded*				*Discarded*			
Video	W-fixed	*Discarded*				*Discarded*			
	S-fixed	*Discarded*			*Discarded*				
Audio	Long	*Discarded*						*Discarded*	
	Short		*Discarded*					*Discarded*	

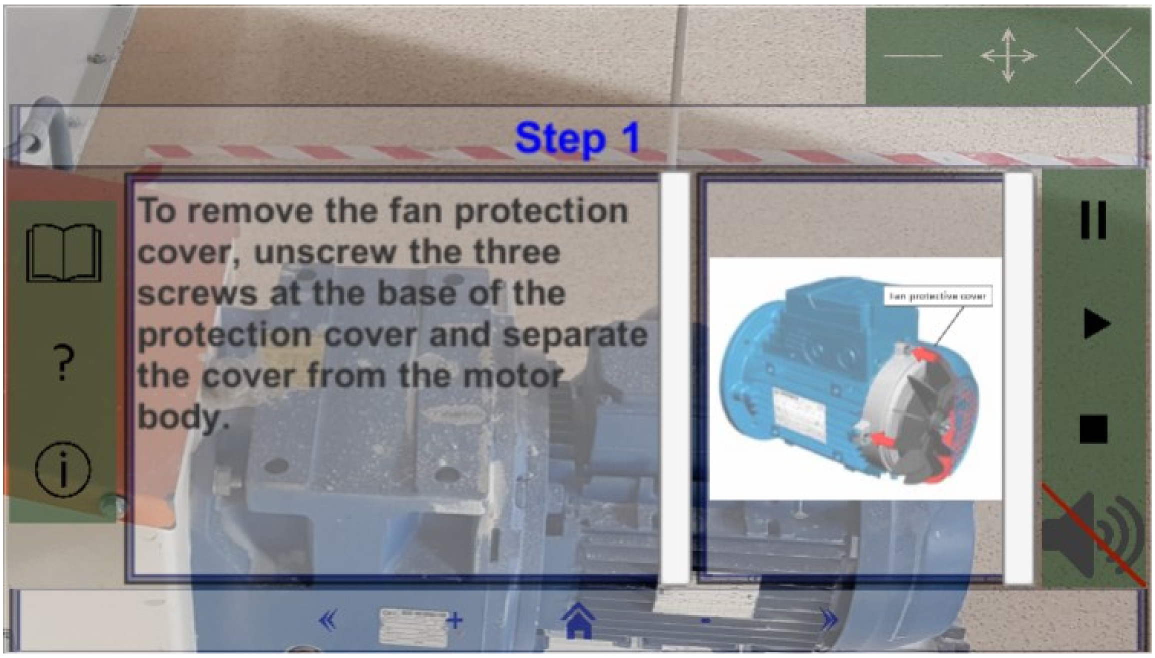
6.5.3. Active AR Output

The Active AR output application, running on the AR device, displays the technical assets according to a context-dependent layout. To test this concept, we designed two GUI layouts: a small and a large one (see Fig. 48 and Fig. 49). The small one is suggested for expert operators who receive less detailed information. In this way, there is less occlusion of the real world and this is particularly crucial for the HoloLens due to the limited FOV. The visual assets were arranged into two main areas in the layouts: one for text assets and the other for non-text assets. The GUI provides other features as playback control buttons for the audio assets, help button, navigation bar, and so on.



To remove the fan protection cover, unscrew the three screws at the base of the protection cover and separate the cover from the motor body.

Fig. 48 Small GUI layout for HoloLens.



To remove the fan protection cover, unscrew the three screws at the base of the protection cover and separate the cover from the motor body.

Fig. 49 Large GUI layout for HHD.

6.6. Results

We tested the effectiveness of the proposed CATIM verifying its interactivity by measuring two execution times: the reasoning time and the turnaround time. The reasoning time we define as the time the back-end takes to load all required information into memory and then to send the recommended response to front-end. The turnaround time we define as the elapsed time from which the user requests information to the time in which technical assets are rendered on AR user interface. During this time, users must wait for CATIM and thus cannot perform any interaction. Reasoning and turnaround time were measured without considering network communication time, as all assets are stored in the back-end which runs on the local network. We recorded reasoning and turnaround time seven times for each AR device. The mean reasoning time for the 28 (7 trial × 4 devices) measures was 18.3 ms. The mean turnaround times for the four devices are reported in Fig. 50 and suggest that CATIM can support highly-interactive user experiences. We observed that the ranking of times measured for the smartphones match that of the AnTuTu benchmark, as expected. Finally, we observed that the standard deviations are higher on smartphones that have many external processes and thus their execution times may vary.

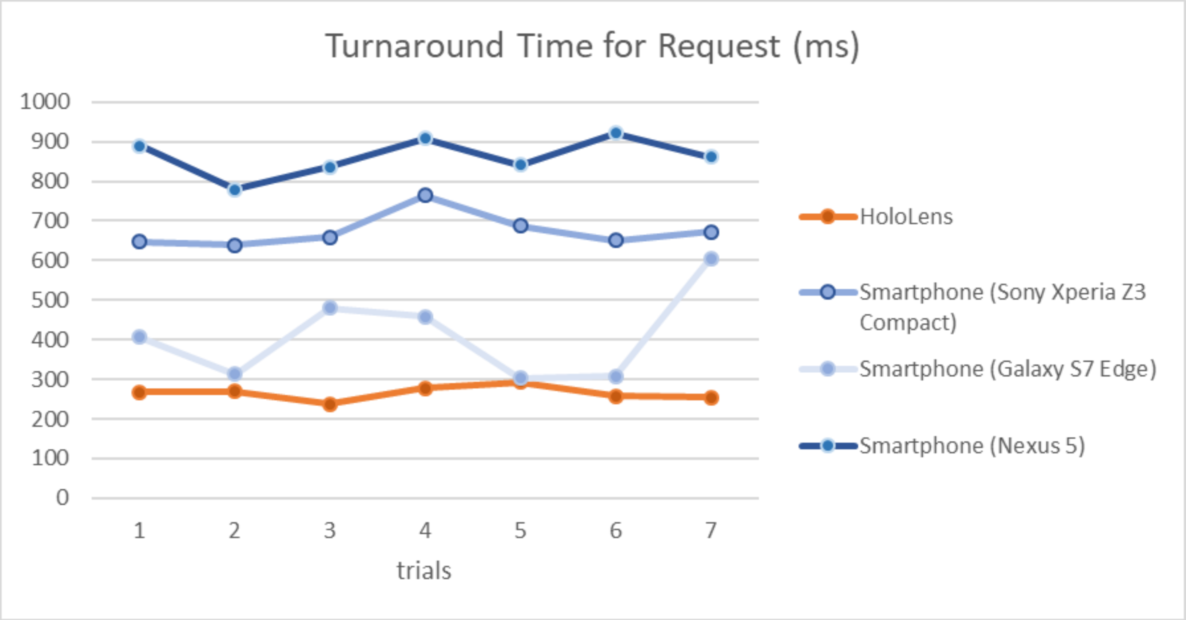


Fig. 50 Results about CATIM turnaround times for each device used in the test. The times (all below 1000 ms) reported allow an interactive behavior of the system.

These results suggest that CATIM can support interactive system performance rates, showing acceptable performance in terms of turnaround time over a series of tested devices. While we used a reduced context dataset for this work, the system is designed in a way to maintain interactive processing speeds with larger datasets. The properties of the recommendation system allow it to be scalable, eventually dividing the ontologies into knowledge subsets, while the visualization engine does not depend in any way on the system size. For this purpose, a valuable attribute of the system would be the possibility of automatically populating the ontology with a set of technical manuals, by taking them from large datasets (e.g., IFixit), often written in authoring-oriented standards, like oManual [228], DITA [229] or DocBook [230].

As to the context-awareness capability, we tested all the possible context vectors (i.e., activity/operator/environment attribute combination) verifying which technical assets are recommended by CATIM. The results were consistent with what we would predict according to the concept covering rules for the current context. As expected, the recommendation process removes all the asset types which create contradictions with the current context. Some of the responses reported more than one compatible asset, suggested in decreasing order of importance, thus only the first asset was automatically shown, while the others were hidden (but still manually selectable by the operator if desired). In the case of an expert user, the number of technical information assets suggested is lower, as s/he is expected to need less information to accomplish familiar and common tasks.

Comparing CATIM with other context-aware AR systems presented in the literature, we can say that CATIM can: (i) manage all the possible types of visual assets; (ii) consider the ‘people’ factor; and (iii) implement user-defined rules for the management of visual assets. This last aspect is crucial because when established standard about the visualization of technical documentation in AR will be available [231], it would be possible to integrate them in the reasoner for the right choice of technical assets.

By taking a closer look at the results for the context with a novice operator, we can observe that the world-fixed assets are always returned by the system in a specific order (CAD > Video > Photo). This behavior is due to the limited description we adopted for this experiment: if two asset types have the same covering on the current context, the one first declared in the ontology that is chosen. This feature of CATIM can be used to establish an order of importance inside the ontology, which can derive from a finer user profiling that also considers user preferences for visual assets. User profiling is normally used in everyone’s everyday life (e.g., in web browsing, banks) even if issues related to ethics and acceptable uses of technology will become increasingly critical to its creation and usage. In this prototype, we did not consider ethic issues derived from user profiling. In future works, we will ask for operator permissions to use personal data for the scope of the application, as usually made in other scenarios.

While CATIM was designed to help in the management of technical documentation for AR user interfaces, it can be also be used for the authoring phase because authors can create new manuals with novel technical information assets, describe them in the ontology, and simulate the composition of the manual. Thus, CATIM could be the basis for further implementations and experiments for next-generation operator manuals.

In this work, we describe a novel approach for the implementation of a context-aware technical information manager (CATIM) that acquires context data about activity, operator, and environment, and then based on these data, proposes a dynamic AR user interface tailored to the current operating context. A main contribution of this work is that CATIM can propose dynamically composed AR user interfaces, based on multiple parameters detected from the context in real-time. While we use activity, operator, and environmental parameters in this use case, CATIM is capable of working with arbitrary sets of parameters. Thus, this work can serve as a springboard for other AR user interface researchers looking to create real-time, adaptive AR user interfaces.

In this work, we limited the presentation of our approach to the implementation of CATIM, providing also a first evaluation in the Mill 4.0 scenario to better explain how the system works. We limited the number of variables in the context and their attributes (e.g., expert/novice, smartphone/HoloLens) for the sake of clarity. However, other variables (e.g., operator's language, preference, environment hazards, and so on) and attributes (e.g., other devices as video see-through head worn displays, monitors) can be added to the ontology. We decided to test and validate CATIM with a specific user study in future works, due to the large number of variables to control.

The final objective of the ongoing research would lead to the development of the following two parts: (i) an optimized active AR user interface, not bounded by any fixed layout, capable of interpreting user properties and environment constraints; and, (ii) an automatic recognition of technical documentation needed in a certain context. As to the dynamic AR interface, the current implementation is bounded to a limited set of fixed layouts even if they are populated dynamically. Future work will include also dynamic arrangement of assets in the interface layout.

Conclusion and future works

In this dissertation, we investigated AR as a means for the presentation of technical information in an industrial scenario. Specifically, we brought AR to a flour milling plant, but the considerations made apply to all industrial scenarios.

As a key enabling technology of I4.0, AR has reached a level of maturity that allows its use only in particular tasks, i.e., where scientific studies have largely demonstrated its benefits. However, what has already been achieved in this field is only an initial step towards the full integration of AR in the factory of the future as it is described in the model of the Industry 4.0 principles.

The results we have obtained from the analysis of the state of the art on IAR interfaces, from the patent analysis conducted on a large sample of patents regarding AR, from the solutions developed; have given encouraging results, nevertheless, further studies are required. We believe, that with our studies, the research field of AR has made small steps forward.

We carried out a systematic literature review of visualization methods for technical instructions in IAR prototypes and concepts for maintenance, assembly, and training procedures. The extensions of each class proposed proved to be mutually exclusive, and jointly exhaustive for all the 348 visual assets analyzed, extracted from 122 selected papers published between 1997 to 2019. We propose a novel classification for IAR technical visual assets according to: (i) what content is displayed via the visual asset, (ii) how the visual asset can convey information, and, (iii) why the visual asset is used.

The main findings can be summarized as follow:

- IAR has a positive trend in literature;
- HWDs are trending, spatial AR (to date) has few IAR implementations;
- the number of visual assets in maintenance is higher than assembly and personnel training;
- product model is the most common visual asset, followed by text and auxiliary model;
- the most-used visual asset in maintenance is text, in assembly product model, and for personnel training the auxiliary model;
- product model and auxiliary models are almost always world-fixed;
- technical drawing, drawings, photographs, and video are usually screen-fixed assets;

- color coding is uncommon;
- animation is uncommon and limited to product model and auxiliary model only; and;
- for locating, the most common visual asset is the auxiliary model, for operating the product model, and for checking, the text.

Even though we analyzed the literature specific to applications of AR in maintenance, assembly, and training, the classification proposed herein could be applied to other industrial fields such as manufacturing, construction, plant layout, and so on. Furthermore, it can be effective for other domains such as medical applications, cultural heritage, transportation, etc.

This work may further help the community (e.g., researchers, developers, standard technical committees) to better understand the practices and trends that, with further scientific support, may eventually lead to consolidated guidelines for IAR interface design.

The research on visual assets was also helped by the findings of a survey with potential IAR technical writers on the preference of visual assets for IAR interfaces. For all forms of information except for "notification" where it cannot be used, the product model turned out to be the most favored. In this situation, users recommended the use of visual pictorial tools such as drawings, signs, and auxiliary model. Alternatives to the product model were also suggested: "identity" video and image, "order" auxiliary model, "way to" video and auxiliary model, "orientation" video. Text was the least favored visual asset.

We also approached AR from a totally new aspect. In fact, the contribution of patent analysis is the investigation of technology trends, with results that can be useful to researchers and developers for technical guidance, but also to policymakers, managers, and entrepreneurs for technology scouting and forecasting. Our study found that AR technology development has increased especially in the last decade. In particular, we evidenced a remarkable steady of 82% annual growth rate of the number of granted patents after 2012. From geographical distribution, we found that North America is the leader (68%); Asia (18%) and Europe (13%) are lagging behind despite dedicated Industry 4.0 policies actuated by the governments. Another nontrivial result is the incoherency between the owners of a high quantity of patents and those highly impacting. In fact, only Microsoft Corporation and Amazon Technologies are at the same time in the top 10 of the most patent-intensive organizations and the top 10 of highly impacting organizations. Moreover, the majority of the patents are owned by companies, albeit some of the highly impacting ones come from universities or research centers. These findings provide theoretical, managerial, and policy implications for future research activities in the AR domain.

An AR application for an industrial scenario of a flour milling plant was also implemented and evaluated by us. The application enhances the P&ID of a flour milling plant to assist operators with the task of data retrieval. Through a user study aimed at comparing the AR application for current practice, based on paper documentation, for an information retrieval task within a maintenance procedure. For this type of task, we verified the results already obtained in the literature. The results of the research showed that in terms of time reduction and usability, AR is successful for this role. With both a tablet and a smartphone, the AR framework was tested, but the results showed that using the tablet did not boost user efficiency in terms of time, error rate, and usability. Future studies on this application will involve the synchronization of engineering data through a dynamic graph-based model, including P&ID. It would be possible to both visualize and control the P&ID and the associated technical details in real time with the combination of the two frameworks. Indeed, a future phase of this work, which we have already planned, is to present dynamic details such as the plant Key Performance Indicators (KPI).

Finally, for the implementation of a context-aware technical information manager (CATIM), we define a novel approach that acquires context data on operation, operator, and setting, and then, based on these data, proposes a dynamic AR user interface tailored to the current operating context. The key contribution of this research is that CATIM may propose user interfaces with dynamically composed AR, based on multiple parameters detected from the context in real-time. We also created a simpler ontology, based on Mill 4.0 scenario, to drive the active AR interface, thanks to the reasoning strategies used. This ontology for technical documentation works well with the reasoner. It allows great flexibility without having the need of an expert knowledge engineer to adjust the whole ontology at every new update. However, this may also result in a loss of expressiveness, compared to that allowed by other knowledge architectures. Thus, for next-generation operator manuals, CATIM may be the basis for further implementations and experiments. Without the need for explicit manual analysis, these next-generation manuals will be capable of delivering technical knowledge and could view essential technical information in the most suitable way possible, leveraging virtual and augmented reality technologies.

La borsa di dottorato è stata cofinanziata con risorse del
Programma Operativo Nazionale Ricerca e Innovazione 2014-2020 (CCI 2014IT16M2OP005),
Fondo Sociale Europeo, Azione I.1 “Dottorati Innovativi con caratterizzazione Industriale”

UNIONE EUROPEA
Fondo Sociale Europeo

Ministero dell'Istruzione,
dell'Università e della Ricerca

PON
RICERCA
E INNOVAZIONE
2014 - 2020

Acknowledgements

At the end of this journey, I wanted to thank all the people who supported me:

- The start-up Idea 75 that hosted me during my PhD period in the company;
- The Narvis Lab at the Technical University of Munich for hosting me during my PhD period abroad;
- The start-up Idea75 and the Casillo group that cooperated at the realization of the AR framework for P&ID and for CATIM;
- The Italian Ministry of Education, University and Research under the Programma Operativo Nazionale Ricerca e Innovazione 2014-2020;
- All the people that were part of VR3Lab in these three years: Vito Modesto Manghisi, Michele Gattullo and Antonio Boccaccio. As friends, they supported me facing the difficulties of my PhD experience, and for the valuable suggestions;
- All my cohautors;
- All the undergraduates supported in these years.

I thank all my family and my friends for the moral support in the tough moments of this journey.

Finally, my supervisor Prof. Antonio E. Uva and professors: Michele Fiorentino and Giuseppe Monno, for all the invaluable guidance given during these three years of my PhD course.

Appendix

Table 1. Top patenting organizations distribution

Assignee (60% all patents)	# patents	# citations	Mean citations	Display device	Tracking	UI	HMD Device	Complex Systems. Methods &Techniques for AR	AR App. Field	Technological diversification
Microsoft Corporation	203	970	4.8	36	27	43	23	60	14	0,8
Sony	73	195	2.7	3	15	12	3	33	7	0,7
International Business Machines	71	71	1	5	9	3	2	46	6	0,54
QUALCOMM Incorporated	64	155	2.4	1	16	19	2	23	3	0,71
Samsung Electronics Co.. Ltd.	59	84	1.4	11	6	3	0	32	7	0,63
Magic Leap. Inc.	51	118	2.3	16	7	4	6	18	0	0,72
Amazon Technologies	49	226	4.6	13	7	9	0	16	4	0,75
Intel Corporation	49	71	1.4	2	5	4	0	34	4	0,48
Empire Technology Develoment LLC	48	58	1.2	3	11	5	1	25	3	0,64

Assignee (60% all patents)	# patents	# citations	Mean citations	Display device	Tracking	UI	HMD Device	Complex Systems. Methods &Techniques for AR	AR App. Field	Technological diversification
DAQRI. LLC	45	22	0.5	2	7	5	7	22	2	0,68
Siemens AG	41	606	14.8	1	11	10	1	7	11	0,75
DISNEY ENTERPRISES. INC.	37	65	1.8	4	2	6	1	15	9	0,71
Google Inc	35	397	11.3	7	3	10	3	9	3	0,77
LG Electronics Inc.	35	129	3.7	3	2	2	11	13	4	0,72
NOKIA CORPORATION	31	52	1.7	1	1	9	0	18	2	0,55
Nant Holdings IP. LLC	21	145	6.9	1	6	1	0	9	4	0,66
A9.COM. INC.	21	29	1.4	0	6	5	0	6	4	0,71
Apple. Inc.	20	96	4.8	3	6	0	0	10	1	0,6
Bally Gaming. Inc.	20	37	1.85	0	1	0	0	3	16	0,32
AT&T	18	15	0.8	0	0	0	0	15	3	0,26
Meta Company	16	3	0.2	3	0	8	1	4	0	0,61

Assignee (60% all patents)	# patents	# citations	Mean citations	Display device	Tracking	UI	HMD Device	Complex Systems. Methods &Techniques for AR	AR App. Field	Technological diversification
Bank of America Corporation	16	85	5.3	0	1	0	0	9	6	0,51
Electronics and Telecommunications Research Institute	16	27	1.7	0	2	1	0	5	8	0,59
Information Decision Technologies LLC	16	255	15.9	0	2	1	0	2	11	0,46
The Boeing Company	15	23	1.5	0	1	0	1	2	11	0,41
SEIKO EPSON CORPORATION	14	0	0	1	2	0	11	0	0	0,33
THINKWARE CORPORATION	14	0	0	0	0	0	0	6	8	0,45
Atheer	13	2	0.2	0	2	6	1	4	0	0,61
Honda Motor Co.. Ltd.	13	25	1.9	2	0	0	0	0	11	0,24

Assignee (60% all patents)	# patents	# citations	Mean citations	Display device	Tracking	UI	HMD Device	Complex Systems. Methods &Techniques for AR	AR App. Field	Technological diversification
Blackberry Limited	12	7	0.6	0	2	2	1	7	0	0,55
IMMERSION CORPORATION	11	8	0.7	7	0	1	0	3	0	0,47
Elwha LLC	11	8	0.7	0	0	2	0	9	0	0,27
Capital One Services. LLC	11	3	0.3	0	5	0	0	4	2	0,57
eBay Inc.	11	25	2.3	0	0	0	0	7	4	0,42
Osterhout Group. Inc.	11	29	2.6	6	1	0	3	1	0	0,56
Hyundai Motor Company	11	5	0.5	2	0	1	0	1	7	0,5
XEROX Corporation	11	215	19.5	0	3	0	0	8	0	0,36
Bentley Systems. Incorporated	11	13	1.2	0	3	0	0	6	2	0,54
Metaio GmbH	11	360	32.7	0	9	0	0	2	0	0,27
Rawles LLC	11	75	6.8	3	3	2	0	3	0	0,68

Assignee (60% all patents)	# patents	# citations	Mean citations	Display device	Tracking	UI	HMD Device	Complex Systems. Methods &Techniques for AR	AR App. Field	Technological diversification
Wells Fargo Bank. N.A.	10	3	0.3	0	0	0	0	4	6	0,43
HAND HELD PRODUCTS. INC.	10	170	17.0	0	1	0	0	2	7	0,41
FUJITSU LIMITED	10	2	0.2	4	3	0	0	2	1	0,63
ABL IP Holding LLC	10	9	0.9	0	6	1	0	1	2	0,52
HERE Global B.V.	10	17	1.7	0	1	2	0	6	1	0,52

Appendix 2: List of Figures

Appendix 3: List of Tables

Bibliography

[1] M. Hermann, T. Pentek, and B. Otto, “Design principles for industrie 4.0 scenarios,” in *System Sciences (HICSS), 2016 49th Hawaii International Conference on*, 2016, pp. 3928–3937.

[2] A. Barthelmey, D. Störkle, B. Kuhlenkötter, and J. Deuse, “Cyber physical systems for life cycle continuous technical documentation of manufacturing facilities,” *Procedia CIRP*, vol. 17, pp. 207–211, 2014.

[3] D. Schmalstieg and G. Reitmayr, “The World as a User Interface: Augmented Reality for Ubiquitous Computing,” in *Location Based Services and TeleCartography*, Springer Berlin Heidelberg, 2007, pp. 369–391.

[4] M. Lorenz, S. Knopp, and P. Klimant, “Industrial Augmented Reality: Requirements for an Augmented Reality Maintenance Worker Support System,” in *Adjunct Proceedings - 2018 IEEE International Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2018*, 2018, pp. 151–153, doi: 10.1109/ISMAR-Adjunct.2018.00055.

[5] R. T. Azuma, “A Survey of Augmented Reality,” 1997.

[6] J. P. Rolland, R. L. Holloway, and H. Fuchs, “Comparison of optical and video see-through, head-mounted displays,” in *Telemanipulator and Telepresence Technologies*, 1995, vol. 2351, pp. 293–307, doi: 10.1117/12.197322.

[7] A. E. Uva *et al.*, “Design of a projective AR workbench for manual working stations,” in *International Conference on Augmented Reality, Virtual Reality and Computer Graphics*, 2016, pp. 358–367.

[8] R. W. Lindeman, H. Noma, and P. G. De Barros, “Hear-through and mic-through augmented reality: Using bone conduction to display spatialized audio,” *2007 6th IEEE ACM Int. Symp. Mix. Augment. Reality, ISMAR*, pp. 1–4, 2007, doi: 10.1109/ISMAR.2007.4538843.

[9] O. Bau and I. Poupyrev, “REVEL: Tactile Feedback Technology for Augmented Reality,” *ACM Trans. Graph.*, vol. 31, no. 4, pp. 89:1--89:11, 2012, doi: 10.1145/2185520.2185585.

[10] T. Narumi, S. Nishizaka, T. Kajinami, T. Tanikawa, and M. Hirose, “Augmented reality flavors: Gustatory display based on Edible Marker and cross-modal interaction,” in *Conference on Human Factors in Computing Systems - Proceedings*, 2011, pp. 93–102, doi: 10.1145/1978942.1978957.

[11] I. Rabbi and S. Ullah, “A survey on augmented reality challenges and tracking,” *Acta Graph. Znan. časopis za Tisk. i Graf. Komun.*, vol. 24, no. 1–2, pp. 29–46, 2013.

[12] F. N. Afif, A. H. Basori, and N. Saari, “Vision based tracking technology for augmented reality: A survey,” *Int. J. Interact. Digit. Media*, vol. 1, no. 1, pp. 46–49, 2013.

[13] D. Wagner, T. Langlotz, and D. Schmalstieg, “Robust and unobtrusive marker tracking on mobile phones,” *Proc. - 7th IEEE Int. Symp. Mix. Augment. Real. 2008, ISMAR 2008*, pp. 121–124, 2008, doi: 10.1109/ISMAR.2008.4637337.

[14] S. You and U. Neumann, “Fusion of vision and gyro tracking for robust augmented reality registration,” in *Proceedings IEEE Virtual Reality 2001*, 2001, pp. 71–78.

[15] F. Liarokapis, “An augmented reality interface for visualizing and interacting with virtual content,” *Virtual Real.*, vol. 11, no. 1, pp. 23–43, Mar. 2007, doi: 10.1007/s10055-006-0055-1.

[16] T. Piumsomboon, A. Clark, M. Billinghurst, and A. Cockburn, “User-defined gestures for augmented reality,” in *IFIP Conference on Human-Computer Interaction*, 2013, pp. 282–299.

[17] I. Poupyrev, D. S. Tan, M. Billinghurst, H. Kato, H. Regenbrecht, and N. Tetsutani, “Developing a generic augmented-reality interface,” *Computer (Long. Beach. Calif).*, vol. 35, no. 3, pp. 44–50, 2002, doi: 10.1109/2.989929.

[18] V. Buchmann, S. Violich, M. Billinghurst, and A. Cockburn, “FingARtips: gesture based direct manipulation in Augmented Reality,” in *Proceedings of the 2nd international conference on Computer graphics and interactive techniques in Australasia and South East Asia*, 2004, pp. 212–221.

[19] M. Billinghurst, A. Clark, and G. Lee, “A survey of augmented reality,” *Found. Trends Human-Computer Interact.*, vol. 8, no. 2–3, pp. 73–272, 2014, doi: 10.1561/1100000049.

[20] P. Fite-Georgel, “Is there a reality in industrial augmented reality?,” in *2011 10th ieee international symposium on mixed and augmented reality*, 2011, pp. 201–210.

[21] F. Longo, L. Nicoletti, A. P.-C. & industrial engineering, and undefined 2017, “Smart operators in industry 4.0: A human-centered approach to enhance operators’ capabilities and competencies within the new smart factory context,” *Elsevier*.

[22] C. Rolim, D. Schmalstieg, D. Kalkofen, and V. Teichrieb, “[POSTER] Design Guidelines for Generating Augmented Reality Instructions,” in *2015 IEEE International Symposium on Mixed and Augmented Reality*, 2015, pp. 120–123.

[23] M. Lechner, “ARML 2.0 in the context of existing AR data formats,” in *Software Engineering and Architectures for Realtime Interactive Systems (SEARIS), 2013 6th Workshop on*, 2013, pp. 41–47.

[24] B. MacIntyre, A. Hill, H. Rouzati, M. Gandy, and B. Davidson, “The Argon AR Web Browser and standards-based AR application environment,” in *Mixed and Augmented Reality (ISMAR), 2011 10th IEEE International Symposium on*, 2011, pp. 65–74.

[25] 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.

[26] 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,” in *2013 IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2013*, 2013, pp. 251–252, doi: 10.1109/ISMAR.2013.6671790.

[27] R. Radkowski, J. Herrema, and J. Oliver, “Augmented reality-based manual assembly support with visual features for different degrees of difficulty,” *Int. J. Hum. Comput. Interact.*, vol. 31, no. 5, pp. 337–349, 2015.

[28] T. C. Endsley, K. A. Sprehn, R. M. Brill, K. J. Ryan, E. C. Vincent, and J. M. Martin, “Augmented reality design heuristics: Designing for dynamic interactions,” in *Proceedings of the Human Factors and Ergonomics Society*, 2017, vol. 2017-Octob, no. 1, pp. 2100–2104, doi: 10.1177/1541931213602007.

[29] S. Werrlich, P. A. Nguyen, A. D. Daniel, C. E. F. Yanez, C. Lorber, and G. Notni, “Design recommendations for HMDbased assembly training tasks,” in *CEUR Workshop Proceedings*, 2018, vol. 2082, pp. 58–68.

[30] M. Funk, T. Kosch, and A. Schmidt, “Interactive worker assistance: comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions,” in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, 2016, pp. 934–939.

[31] R. T. Azuma, “A survey of augmented reality,” *Presence Teleoperators \& Virtual Environ.*, vol. 6, no. 4, pp. 355–385, 1997.

[32] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre, “Recent advances in augmented reality,” *IEEE Comput. Graph. Appl.*, vol. 21, no. 6, pp. 34–47, 2001, doi: 10.1109/38.963459.

[33] D. W. F. Van Krevelen and R. Poelman, “A survey of augmented reality technologies, applications and limitations,” *Int. J. virtual Real.*, vol. 9, no. 2, p. 1, 2010.

[34] 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.

[35] M. Billinghurst, A. Clark, G. Lee, and others, "A survey of augmented reality," *Found. Trends®in Human--Computer Interact.*, vol. 8, no. 2–3, pp. 73–272, 2015.

[36] F. Zhou, H. B. L. Dun, and M. Billinghurst, "Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR," in *Proceedings - 7th IEEE International Symposium on Mixed and Augmented Reality 2008, ISMAR 2008*, 2008, pp. 193–202, doi: 10.1109/ISMAR.2008.4637362.

[37] K. Kim, M. Billinghurst, G. Bruder, H. B. L. Duh, and G. F. Welch, "Revisiting trends in augmented reality research: A review of the 2nd Decade of ISMAR (2008-2017)," *IEEE Trans. Vis. Comput. Graph.*, vol. 24, no. 11, pp. 2947–2962, Nov. 2018, doi: 10.1109/TVCG.2018.2868591.

[38] 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.

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

[40] A. Syberfeldt, O. Danielsson, and P. Gustavsson, "Augmented Reality Smart Glasses in the Smart Factory: Product Evaluation Guidelines and Review of Available Products," *IEEE Access*, vol. 5. pp. 9118–9130, 2017, doi: 10.1109/ACCESS.2017.2703952.

[41] S. Rankohi and L. Waugh, "Review and analysis of augmented reality literature for construction industry," *Vis. Eng.*, vol. 1, no. 1, p. 9, 2013.

[42] G. Dini and M. Dalle Mura, "Application of augmented reality techniques in through-life engineering services," *Procedia CIRP*, vol. 38, pp. 14–23, 2015.

[43] P. Fraga-Lamas, T. M. Fernández-Caramés, Ó. Blanco-Novoa, and M. A. Vilar-Montesinos, "A Review on Industrial Augmented Reality Systems for the Industry 4.0

Shipyard," *IEEE Access*, vol. 6, pp. 13358–13375, 2018.

[44] 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, pp. 215–228, 2018, doi: 10.1016/j.rcim.2017.06.002.

[45] E. Bottani and G. Vignali, "Augmented reality technology in the manufacturing industry: A review of the last decade," *IISE Trans.*, vol. 51, no. 3, pp. 284–310, 2019.

[46] E. Kruijff, J. E. Swan, and S. Feiner, "Perceptual issues in augmented reality revisited," in *Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on*, 2010, pp. 3–12.

[47] J. P. Rolland, K. P. Thompson, A. Bauer, H. Urey, and M. Thomas, "See-through head-worn display (HWD) architectures," *Handb. Vis. Disp. Technol.*, pp. 1–32, 2016.

[48] J. E. Swan and J. L. Gabbard, "Survey of user-based experimentation in augmented reality," in *Proceedings of 1st International Conference on Virtual Reality*, 2005, pp. 1–9.

[49] A. Dey, M. Billinghurst, R. W. Lindeman, and J. E. Swan, "A systematic review of 10 Years of Augmented Reality usability studies: 2005 to 2014," *Front. Robot. AI*, vol. 5, no. APR, 2018, doi: 10.3389/frobt.2018.00037.

[50] A. Booth, A. Sutton, and D. Papaioannou, "Systematic approaches to a successful literature review," 2016.

[51] J. Zauner, M. Haller, A. Brandl, and W. Hartman, "Authoring of a mixed reality assembly instructor for hierarchical structures," in *Proceedings - 2nd IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR 2003*, 2003, pp. 237–246, doi: 10.1109/ISMAR.2003.1240707.

[52] G. Riexinger, A. Kluth, M. Olbrich, J. D. Braun, and T. Bauernhansl, "Mixed Reality for On-Site Self-Instruction and Self-Inspection with Building Information Models," in *Procedia CIRP*, 2018, vol. 72, pp. 1124–1129, doi: 10.1016/j.procir.2018.03.160.

[53] S. Werrlich, E. Eichstetter, K. Nitsche, and G. Notni, “An Overview of Evaluations Using Augmented Reality for Assembly Training Tasks,” *Int. J. Comput. Inf. Eng.*, vol. 11, no. 10, pp. 1129–1135, 2017.

[54] J. Wither, S. DiVerdi, and T. Höllerer, “Annotation in outdoor augmented reality,” *Comput. \& Graph.*, vol. 33, no. 6, pp. 679–689, 2009.

[55] A. Marradi, “Classification, typology, taxonomy,” *Qual. Quant.*, vol. 24, no. 2, p. 129, 1990, doi: 10.1007/BF00209548.

[56] R. Pierdicca, E. Frontoni, R. Pollini, M. Trani, and L. Verdini, “The use of augmented reality glasses for the application in industry 4.0,” in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2017, vol. 10324 LNCS, pp. 389–401, doi: 10.1007/978-3-319-60922-5_30.

[57] A. E. Uva, M. Gattullo, V. M. Manghisi, D. Spagnulo, G. L. Cascella, and M. Fiorentino, “Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations,” *Int. J. Adv. Manuf. Technol.*, vol. 94, no. 1–4, pp. 509–521, Jan. 2018, doi: 10.1007/s00170-017-0846-4.

[58] “iFixit: The Free Repair Manual, https://www.ifixit.com/ last accessed (June, 11, 2019).” 2019.

[59] 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, doi: 10.1016/j.robot.2012.09.013.

[60] M. Aleksy, E. Vartiainen, V. Domova, and M. Naedele, “Augmented reality for improved service delivery,” in *Proceedings - International Conference on Advanced Information Networking and Applications, AINA*, 2014, pp. 382–389, doi: 10.1109/AINA.2014.146.

[61] S. Werrlich, A. Daniel, A. Ginger, P. A. Nguyen, and G. Notni, “Comparing HMD-Based and Paper-Based Training,” in *Proceedings of the 2018 IEEE International Symposium*

on Mixed and Augmented Reality, ISMAR 2018, 2019, pp. 134–142, doi: 10.1109/ISMAR.2018.00046.

[62] G. Vignali, M. Bertolini, E. Bottani, L. Di Donato, A. Ferraro, and F. Longo, “Design and testing of an augmented reality solution to enhance operator safety in the food industry,” *Int. J. Food Eng.*, vol. 14, no. 2, Feb. 2018, doi: 10.1515/ijfe-2017-0122.

[63] C. S. Peirce, “Collected writings (8 vols.),” *Harvard Univ. Press. Cambridge*, vol. 58, 1931.

[64] ISO, “International standard for safety colours and safety signs: ISO 3864.” International Standards Organization Switzerland, 1984.

[65] G. W. Scurati, M. Gattullo, M. Fiorentino, F. Ferrise, M. Bordegoni, and A. E. Uva, “Converting maintenance actions into standard symbols for Augmented Reality applications in Industry 4.0,” *Comput. Ind.*, vol. 98, pp. 68–79, 2018, doi: 10.1016/j.compind.2018.02.001.

[66] M. Abramovici, M. Wolf, S. Adwernat, and M. Neges, “Context-aware Maintenance Support for Augmented Reality Assistance and Synchronous Multi-user Collaboration,” in *Procedia CIRP*, 2017, vol. 59, pp. 18–22, doi: 10.1016/j.procir.2016.09.042.

[67] J. Wang, Y. Feng, C. Zeng, and S. Li, “An augmented reality based system for remote collaborative maintenance instruction of complex products,” in *Automation Science and Engineering (CASE), 2014 IEEE International Conference on*, 2014, pp. 309–314.

[68] N. Pathomaree and S. Charoenseang, “Augmented reality for skill transfer in assembly task,” in *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*, 2005, vol. 2005, pp. 500–504, doi: 10.1109/ROMAN.2005.1513829.

[69] M. D. Mura, G. Dini, and F. Failli, “An Integrated Environment Based on Augmented Reality and Sensing Device for Manual Assembly Workstations,” in *Procedia CIRP*, 2016, vol. 41, pp. 340–345, doi: 10.1016/j.procir.2015.12.128.

[70] 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, Apr. 2008, doi: 10.1080/00207540600972935.

[71] ISO, "Technical drawings -- General principles of presentation -- Part 1: Introduction and index." International Standards Organization Switzerland, 2003.

[72] ANSI. and A. S. of Mechanical Engineers, *ASME Y14. 41-2003: Digital Product Definition Data Practices: An American National Standard*. American Society of Mechanical Engineers, 2003.

[73] T. Engelke, J. Keil, P. Rojtberg, F. Wientapper, M. Schmitt, and U. Bockholt, "Content first - A concept for industrial augmented reality maintenance applications using mobile devices," in *Proceedings of the 6th ACM Multimedia Systems Conference, MMSys 2015*, 2015, pp. 105–111, doi: 10.1145/2713168.2713169.

[74] J. Zhang, S. K. Ong, and A. Y. C. Nee, "RFID-assisted assembly guidance system in an augmented reality environment," *Int. J. Prod. Res.*, vol. 49, no. 13, pp. 3919–3938, Jul. 2011, doi: 10.1080/00207543.2010.492802.

[75] C. J. Chen, J. Hong, and S. F. Wang, "Automated positioning of 3D virtual scene in AR-based assembly and disassembly guiding system," *Int. J. Adv. Manuf. Technol.*, vol. 76, no. 5–8, pp. 753–764, 2014, doi: 10.1007/s00170-014-6321-6.

[76] R. Radkowski, T. Garrett, J. Ingebrand, and D. Wehr, "Trackingexpert - A versatile tracking toolbox for augmented reality," in *Proceedings of the ASME Design Engineering Technical Conference*, 2016, vol. 1B-2016, doi: 10.1115/DETC2016-60401.

[77] J. L. Gabbard, G. M. Fitch, and H. Kim, "Behind the Glass: Driver challenges and opportunities for AR automotive applications," *Proc. IEEE*, vol. 102, no. 2, pp. 124–136, 2014.

[78] A. ANSI, "ASME A13. 1—Scheme for the Identification of Piping Systems," *Am. Soc. Mech. Eng.*, 2007.

[79] H. Hirano, *5 Pillars of the Visual Workplace*. 1995.

[80] S. Stork and A. Schubö, “Human cognition in manual assembly: Theories and applications,” *Adv. Eng. Informatics*, vol. 24, no. 3, pp. 320–328, 2010.

[81] S. J. Henderson and S. K. Feiner, “Augmented reality in the psychomotor phase of a procedural task,” in *2011 10th IEEE International Symposium on Mixed and Augmented Reality*, 2011, pp. 191–200.

[82] J. Y. Lee and G. Rhee, “Context-aware 3D visualization and collaboration services for ubiquitous cars using augmented reality,” *Int. J. Adv. Manuf. Technol.*, vol. 37, no. 5–6, pp. 431–442, 2008.

[83] G. Schall *et al.*, “Handheld augmented reality for underground infrastructure visualization,” *Pers. ubiquitous Comput.*, vol. 13, no. 4, pp. 281–291, 2009.

[84] S. Kahn, H. Wuest, D. Stricker, and D. W. Fellner, “3D discrepancy check via augmented reality,” in *9th IEEE International Symposium on Mixed and Augmented Reality 2010: Science and Technology, ISMAR 2010 - Proceedings*, 2010, pp. 241–242, doi: 10.1109/ISMAR.2010.5643587.

[85] B. Kerbl, D. Kalkofen, M. Steinberger, and D. Schmalstieg, “Interactive Disassembly Planning for Complex Objects,” in *Computer Graphics Forum*, 2015, vol. 34, no. 2, pp. 287–297.

[86] R. Grasset, T. Langlotz, D. Kalkofen, M. Tatzgern, and D. Schmalstieg, “Image-driven view management for augmented reality browsers,” in *Mixed and Augmented Reality (ISMAR), 2012 IEEE International Symposium on*, 2012, pp. 177–186.

[87] M. Gattullo, A. E. Uva, M. Fiorentino, and J. L. Gabbard, “Legibility in Industrial AR: Text Style, Color Coding, and Illuminance,” *IEEE Comput. Graph. Appl.*, vol. 35, no. 2, pp. 52–61, 2015, doi: 10.1109/MCG.2015.36.

[88] M. Gattullo, G. W. Scurati, A. Evangelista, F. Ferrise, M. Fiorentino, and A. E. Uva, “Informing the Use of Visual Assets in Industrial Augmented Reality,” in *Lecture Notes in Mechanical Engineering*, 2020, pp. 106–117, doi: 10.1007/978-3-030-31154-4_10.

[89] E. Kruijff, J. E. Swan, and S. Feiner, “Perceptual issues in augmented reality revisited,” in *9th IEEE International Symposium on Mixed and Augmented Reality 2010: Science and Technology, ISMAR 2010 - Proceedings*, 2010, pp. 3–12, doi: 10.1109/ISMAR.2010.5643530.

[90] M. Gattullo, G. W. Scurati, A. Evangelista, F. Ferrise, M. Fiorentino, and A. E. Uva, “Informing the Use of Visual Assets in Industrial Augmented Reality,” in *Lecture Notes in Mechanical Engineering*, 2020, pp. 106–117, doi: 10.1007/978-3-030-31154-4_10.

[91] N. Navab, “Developing killer apps for industrial augmented reality,” *IEEE Comput. Graph. Appl.*, vol. 24, no. 3, pp. 16–20, May 2004, doi: 10.1109/MCG.2004.1297006.

[92] C. Peirce, “Collected writings (8 vols.),” *Harvard Univ. Press. Cambridge*, vol. 58, 1931.

[93] R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi, “A systematic review of augmented reality applications in maintenance,” *Robotics and Computer-Integrated Manufacturing*, vol. 49. pp. 215–228, 2018, doi: 10.1016/j.rcim.2017.06.002.

[94] R. Radkowski, J. Herrema, and J. Oliver, “Augmented Reality-Based Manual Assembly Support With Visual Features for Different Degrees of Difficulty,” *Int. J. Hum. Comput. Interact.*, vol. 31, no. 5, pp. 337–349, May 2015, doi: 10.1080/10447318.2014.994194.

[95] S. M. Harrison, “Comparison of still, animated, or nonillustrated on-line help with written or spoken instructions in a graphical user interface,” in *Conference on Human Factors in Computing Systems - Proceedings*, 1995, vol. 1, pp. 82–89, doi: 10.1145/223904.223915.

[96] J. Heiser, D. Phan, M. Agrawala, B. Tversky, and P. Hanrahan, “Identification and validation of cognitive design principles for automated generation of assembly instructions,” in *Proceedings of the Workshop on Advanced Visual Interfaces AVI*, 2004, pp. 311–319, doi: 10.1145/989863.989917.

[97] R. E. Mayer, W. Bove, A. Bryman, R. Mars, and L. Tapangco, “When Less is More: Meaningful Learning from Visual and Verbal Summaries of Science Textbook Lessons,” *J. Educ. Psychol.*, vol. 88, no. 1, pp. 64–73, 1996, doi: 10.1037/0022-0663.88.1.64.

[98] P. Thompson, “The digital natives as learners: Technology use patterns and approaches to learning,” *Comput. Educ.*, vol. 65, pp. 12–33, 2013, doi: 10.1016/j.compedu.2012.12.022.

[99] M. Prensky, “Digital Natives, Digital Immigrants,” in *From Digital Natives to Digital Wisdom: Hopeful Essays for 21st Century Learning*, vol. 9, no. 5, MCB University Press, 2014, pp. 67–85.

[100] M. Di Donato, M. Fiorentino, A. E. Uva, M. Gattullo, and G. Monno, “Text legibility for projected Augmented Reality on industrial workbenches,” *Comput. Ind.*, vol. 70, pp. 70–78, Jun. 2015, doi: 10.1016/j.compind.2015.02.008.

[101] V. Manghisi *et al.*, “Predicting text legibility over textured digital backgrounds for a monocular optical see-through display,” *Presence Teleoperators Virtual Environ.*, vol. 26, no. 1, pp. 1–15, Feb. 2017, doi: 10.1162/PRES_a_00285.

[102] M. Gattullo, G. W. Scurati, M. Fiorentino, A. E. Uva, F. Ferrise, and M. Bordegoni, “Towards augmented reality manuals for industry 4.0: A methodology,” *Robot. Comput. Integr. Manuf.*, vol. 56, pp. 276–286, 2019, doi: 10.1016/j.rcim.2018.10.001.

[103] A. E. Uva, M. Gattullo, V. M. Manghisi, D. Spagnulo, G. L. Cascella, and M. Fiorentino, “Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations,” *Int. J. Adv. Manuf. Technol.*, vol. 94, no. 1–4, pp. 509–521, Jan. 2018, doi: 10.1007/s00170-017-0846-4.

[104] Marketsandmarkets, “Market Leader - Augmented Reality and Virtual Reality Market.” [Online]. Available: https://www.marketsandmarkets.com/ResearchInsight/augmented-reality-virtual-reality-market.asp. [Accessed: 14-Oct-2019].

[105] C. Arth and D. Schmalstieg, “Challenges of large-scale augmented reality on smartphones,” *Graz Univ. Technol. Graz*, pp. 1–4, 2011.

[106] K. Kiyokawa, “Trends and vision of head mounted display in augmented reality,” *Proc. - 2012 Int. Symp. Ubiquitous Virtual Reality, ISUVR 2012*, pp. 14–17, 2012, doi:

10.1109/ISUVR.2012.11.

[107] "Microsoft HoloLens." [Online]. Available: https://www.microsoft.com/en-us/hololens. [Accessed: 14-Oct-2019].

[108] "Magic Leap." [Online]. Available: https://www.magicleap.com. [Accessed: 14-Oct-2019].

[109] "Daqri Smart Glasses." [Online]. Available: https://daqri.com/products/smart-glasses/. [Accessed: 14-Oct-2019].

[110] "Epson Moverio." [Online]. Available: https://www.epson.co.uk/products/see-through-mobile-viewer. [Accessed: 14-Oct-2019].

[111] Z. He, X. Sui, G. Jin, and L. Cao, "Progress in virtual reality and augmented reality based on holographic display," *Appl. Opt.*, vol. 58, no. 5, pp. A74--A81, Feb. 2019, doi: 10.1364/AO.58.000A74.

[112] S. M. Ko, W. S. Chang, and Y. G. Ji, "Usability Principles for Augmented Reality Applications in a Smartphone Environment," *Int. J. Human–Computer Interact.*, vol. 29, no. 8, pp. 501–515, 2013, doi: 10.1080/10447318.2012.722466.

[113] N. I. Adhani and R. D. R. Awang, "A survey of mobile augmented reality applications," in *1st International Conference on Future Trends in Computing and Communication Technologies*, 2012, pp. 89–96.

[114] R. T. Azuma, "Augmented reality: Approaches and technical challenges," in *Fundamentals of wearable computers and augmented reality*, CRC Press, 2001, pp. 43–80.

[115] M. Mallem, "Augmented Reality: Issues, trends and challenges," in *2010 2nd International Conference on Image Processing Theory, Tools and Applications*, 2010, p. 8, doi: 10.1109/IPTA.2010.5586829.

[116] G. Papagiannakis, G. Singh, and N. Magnenat-Thalmann, "A survey of mobile and wireless technologies for augmented reality systems," *Comput. Animat. Virtual Worlds*,

vol. 19, no. 1, pp. 3–22, Feb. 2008, doi: 10.1002/cav.221.

[117] F. Zhou, H. B. L. Dun, and M. Billinghurst, “Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR,” in *Proceedings - 7th IEEE International Symposium on Mixed and Augmented Reality 2008, ISMAR 2008*, 2008, pp. 193–202, doi: 10.1109/ISMAR.2008.4637362.

[118] K. Kim, M. Billinghurst, G. Bruder, H. B. L. Duh, and G. F. Welch, “Revisiting trends in augmented reality research: A review of the 2nd Decade of ISMAR (2008-2017),” *IEEE Trans. Vis. Comput. Graph.*, vol. 24, no. 11, pp. 2947–2962, 2018, doi: 10.1109/TVCG.2018.2868591.

[119] M. Mekni and A. Lemieux, “Augmented reality: Applications, challenges and future trends,” *Appl. Comput. Sci.*, pp. 205–214, 2014.

[120] H. Choi, S. Oh, S. Choi, and J. Yoon, “Innovation Topic Analysis of Technology: The Case of Augmented Reality Patents,” *IEEE Access*, vol. 6, pp. 16119–16137, 2018, doi: 10.1109/ACCESS.2018.2807622.

[121] B. Jeong and J. Yoon, “Competitive intelligence analysis of augmented reality technology using patent information,” *Sustain.*, vol. 9, no. 4, 2017, doi: 10.3390/su9040497.

[122] L. Ardito, D. D’Adda, and A. Messeni Petruzzelli, “Mapping innovation dynamics in the Internet of Things domain: Evidence from patent analysis,” *Technol. Forecast. Soc. Change*, vol. 136, pp. 317–330, 2018, doi: 10.1016/j.techfore.2017.04.022.

[123] M. Livingston *et al.*, “An augmented reality system for military operations in urban terrain,” *Engineering*, vol. 2002, no. 1, pp. 1–8, 2002.

[124] T. Höllerer, S. Feiner, T. Terauchi, G. Rashid, and D. Hallaway, “Exploring MARS: Developing indoor and outdoor user interfaces to a mobile augmented reality system,” *Comput. Graph.*, vol. 23, no. 6, pp. 779–785, 1999, doi: 10.1016/S0097-8493(99)00103-X.

[125] M. A. Livingston *et al.*, “Military Applications of Augmented Reality,” in *Handbook of*

Augmented Reality, Springer New York, 2011, pp. 671–706.

[126] E. Zhu, A. Hadadgar, I. Masiello, and N. Zary, "Augmented reality in healthcare education: an integrative review," *PeerJ*, vol. 2, p. e469, 2014.

[127] B. Thomas, B. Close, J. Donoghue, J. Squires, P. De Bondi, and W. Piekarski, "First person indoor/outdoor augmented reality application: ARQuake," in *Personal and Ubiquitous Computing*, 2002, vol. 6, no. 1, pp. 75–86, doi: 10.1007/s007790200007.

[128] S. G. Dacko, "Enabling smart retail settings via mobile augmented reality shopping apps," *Technol. Forecast. Soc. Change*, vol. 124, pp. 243–256, 2017.

[129] M. Y.-C. Yim, S.-C. Chu, and P. L. Sauer, "Is augmented reality technology an effective tool for e-commerce? An interactivity and vividness perspective," *J. Interact. Mark.*, vol. 39, pp. 89–103, 2017.

[130] 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," *Computers in Industry*, vol. 103. Elsevier B.V., pp. 47–71, 01-Dec-2018, doi: 10.1016/j.compind.2018.08.007.

[131] 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, Feb. 2017, doi: 10.1016/j.compind.2016.11.004.

[132] 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, Feb. 2014, doi: 10.1016/j.compind.2013.11.012.

[133] 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, doi: 10.1016/j.compind.2013.11.004.

[134] T. Sielhorst, M. Feuerstein, and N. Navab, "Advanced medical displays: A literature review of augmented reality," *J. Disp. Technol.*, vol. 4, no. 4, pp. 451–467, 2008.

[135] S. M. B. I. Botden and J. J. Jakimowicz, “What is going on in augmented reality simulation in laparoscopic surgery?,” *Surgical Endoscopy*, vol. 23, no. 8. Springer New York LLC, pp. 1693–1700, 2009, doi: 10.1007/s00464-008-0144-1.

[136] E. Z. Barsom, M. Graafland, and M. P. Schijven, “Systematic review on the effectiveness of augmented reality applications in medical training,” *Surg. Endosc.*, vol. 30, no. 10, pp. 4174–4183, Oct. 2016, doi: 10.1007/s00464-016-4800-6.

[137] K. Č. Pucihar and P. Coulton, “Exploring the evolution of mobile augmented reality for future entertainment systems,” *Comput. Entertain.*, vol. 11, no. 2, pp. 1:1--1:16, 2014, doi: 10.1145/2582179.2633427.

[138] J. Paavilainen, H. Korhonen, K. Alha, J. Stenros, E. Koskinen, and F. Mäyrä, “The Pokémon go experience: A location-based augmented reality mobile game goes mainstream,” in *Conference on Human Factors in Computing Systems - Proceedings*, 2017, vol. 2017-May, pp. 2493–2498, doi: 10.1145/3025453.3025871.

[139] D. Schmalstieg and T. Hollerer, *Augmented reality: principles and practice*. Addison-Wesley Professional, 2016.

[140] D. W. F. Van Krevelen, “Augmented Reality: Technologies, Applications, and Limitations,” *Int. J. Virtual Real.*, vol. 9, pp. 1–20, 2010, doi: 10.13140/RG.2.1.1874.7929.

[141] I. M. Cockburn and M. J. MacGarvie, “Patents, thickets and the financing of early-stage firms: Evidence from the software industry,” in *Journal of Economics and Management Strategy*, 2009, vol. 18, no. 3, pp. 729–773, doi: 10.1111/j.1530-9134.2009.00228.x.

[142] D. J. Teece, “Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy,” in *The Transfer and Licensing of Know-How and Intellectual Property: Understanding the Multinational Enterprise in the Modern World*, 2008, pp. 67–88.

[143] R. J. Mann and T. W. Sager, “Patents, venture capital, and software start-ups,” *Res. Policy*,

vol. 36, no. 2, pp. 193–208, Mar. 2007, doi: 10.1016/j.respol.2006.10.002.

[144] W. W. Fisher and F. Oberholzer-Gee, “Strategic management of intellectual property: An integrated approach,” *Calif. Manage. Rev.*, vol. 55, no. 4, pp. 157–183, Jun. 2013, doi: 10.1525/cmr.2013.55.4.157.

[145] J. Henkel, C. Y. Baldwin, and W. Shih, “IP modularity: Profiting from innovation by aligning product architecture with intellectual property,” *Calif. Manage. Rev.*, vol. 55, no. 4, pp. 65–82, Jun. 2013, doi: 10.1525/cmr.2013.55.4.65.

[146] B. P. Abraham and S. D. Moitra, “Innovation assessment through patent analysis,” *Technovation*, vol. 21, no. 4, pp. 245–252, 2001, doi: 10.1016/S0166-4972(00)00040-7.

[147] Z. J. Acs, L. Anselin, and A. Varga, “Patents and innovation counts as measures of regional production of new knowledge,” *Res. Policy*, vol. 31, no. 7, pp. 1069–1085, 2002, doi: 10.1016/S0048-7333(01)00184-6.

[148] D. Archibugi and M. Pianta, “Innovation Surveys and Patents as Technology Indicators: The State of the Art,” in *OECD, Innovation, Patents and Technological Strategies*, 1996, pp. 17–56.

[149] O. Manual, “OECD Patent Statistics Manual,” *OECD Publ.*, 2009.

[150] K. Pavitt, “Patent statistics as indicators of innovative activities: Possibilities and problems,” *Scientometrics*, vol. 7, no. 1–2, pp. 77–99, Jan. 1985, doi: 10.1007/BF02020142.

[151] S. Roper and N. Hewitt-Dundas, “Knowledge stocks, knowledge flows and innovation: Evidence from matched patents and innovation panel data,” *Res. Policy*, vol. 44, no. 7, pp. 1327–1340, 2015, doi: 10.1016/j.respol.2015.03.003.

[152] M. Trajtenberg, “A Penny for Your Quotes: Patent Citations and the Value of Innovations,” *RAND J. Econ.*, vol. 21, no. 1, p. 172, 1990, doi: 10.2307/2555502.

[153] V. Albino, L. Ardito, R. M. Dangelico, and A. Messeni Petruzzelli, “Understanding the development trends of low-carbon energy technologies: A patent analysis,” *Appl. Energy*,

vol. 135, pp. 836–854, 2014, doi: 10.1016/j.apenergy.2014.08.012.

[154] C. Huang, A. Notten, and N. Rasters, “Nanoscience and technology publications and patents: A review of social science studies and search strategies,” *Journal of Technology Transfer*, vol. 36, no. 2. pp. 145–172, Apr-2011, doi: 10.1007/s10961-009-9149-8.

[155] L. Leydesdorff, F. Alkemade, G. Heimeriks, and R. Hoekstra, “Patents as instruments for exploring innovation dynamics: Geographic and technological perspectives on ‘“photovoltaic cells,”’” *Scientometrics*, vol. 102, no. 1, pp. 629–651, 2015, doi: 10.1007/s11192-014-1447-8.

[156] X. Li, H. Chen, Z. Huang, and M. C. Roco, “Patent citation network in nanotechnology (1976-2004),” *Journal of Nanoparticle Research*, vol. 9, no. 3. pp. 337–352, Jun-2007, doi: 10.1007/s11051-006-9194-2.

[157] E. J. Han and S. Y. Sohn, “Technological convergence in standards for information and communication technologies,” *Technol. Forecast. Soc. Change*, vol. 106, pp. 1–10, 2016, doi: 10.1016/j.techfore.2016.02.003.

[158] Lee, Y. Nam, S. Lee, and H. Son, “Determinants of ICT innovations: A cross-country empirical study,” *Technol. Forecast. Soc. Change*, vol. 110, pp. 71–77, Sep. 2016, doi: 10.1016/j.techfore.2015.11.010.

[159] S. H. Chang and C. Y. Fan, “Identification of the technology life cycle of telematics a patent-based analytical perspective,” *Technol. Forecast. Soc. Change*, vol. 105, pp. 1–10, 2016, doi: 10.1016/j.techfore.2016.01.023.

[160] E. Novelli, “An examination of the antecedents and implications of patent scope,” *Res. Policy*, vol. 44, no. 2, pp. 493–507, 2015, doi: 10.1016/j.respol.2014.09.005.

[161] X. Tong and J. D. Frame, “Measuring national technological performance with patent claims data,” *Res. Policy*, vol. 23, no. 2, pp. 133–141, 1994, doi: 10.1016/0048-7333(94)90050-7.

[162] M. H. Huang, H. W. Yang, and D. Z. Chen, “Industry–academia collaboration in fuel

cells: a perspective from paper and patent analysis," *Scientometrics*, vol. 105, no. 2, pp. 1301–1318, Nov. 2015, doi: 10.1007/s11192-015-1748-6.

[163] S. Kim, I. Park, and B. Yoon, "Sao2vec: Development of an algorithm for embedding the subject-action-object (SAO) structure using Doc2Vec," *PLoS One*, vol. 15, no. 2, 2020, doi: 10.1371/journal.pone.0227930.

[164] L. L. Kronemeyer, K. Eilers, M. Wustmans, and M. G. Moehrle, "Monitoring Competitors Innovation Activities: Analyzing the Competitive Patent Landscape Based on Semantic Anchor Points," *IEEE Trans. Eng. Manag.*, 2020, doi: 10.1109/TEM.2019.2958518.

[165] Z. Xie and K. Miyazaki, "Evaluating the effectiveness of keyword search strategy for patent identification," *World Pat. Inf.*, vol. 35, no. 1, pp. 20–30, 2013, doi: 10.1016/j.wpi.2012.10.005.

[166] M. G. Moehrle and H. Caferoglu, "Technological speciation as a source for emerging technologies. Using semantic patent analysis for the case of camera technology," *Technol. Forecast. Soc. Change*, vol. 146, pp. 776–784, 2019, doi: 10.1016/j.techfore.2018.07.049.

[167] K. Guruprasad, P. Kanagavel, K. Srikanth, K. Radhika, and S. Sonal, "Analysis of US Patents Granted to Indian Inventors," *J. Intellect. Prop. Rights*, vol. 08, no. 3, pp. 205–212, 2003.

[168] M. Frank, W. Robert, P. Makowenskyj, K. Walter, A. Thelemann, and G. Dawson, "Capsule body attachment," US 20150108050 A1, 2018.

[169] A. Shubham *et al.*, "Checkout and/or ordering systems and methods," US 20140279191 A1, 2016.

[170] L. Seung-hwan *et al.*, "Method of providing information-of-users' interest when video call is made, and electronic apparatus thereof," US 20140125757 A1, 2016.

[171] Rovira; Luis A., "Subscriber television system user interface with a virtual reality media space," 6,795,972, 2004.

[172] H. B. Kenneth and C. St. John, "Method and system for calibrating a virtual reality

system," US 20160343167 A1, 2019.

[173] Nadler; Ingo, "Virtual reality communication systems and methods thereofo Title," US 20170026635 A1, 2016.

[174] D. Harhoff, F. Narin, F. M. Scherer, and K. Vopel, "Citation frequency and the value of patented inventions," *Rev. Econ. Stat.*, vol. 81, no. 3, pp. 511–515, Aug. 1999, doi: 10.1162/003465399558265.

[175] D. Wagner and D. Schmalstieg, "ARToolKitPlus for Pose Tracking on Mobile Devices," *Proc. 12th Comput. Vis. Winter Work.*, no. May, 2007.

[176] I. E. Sutherland, "A head-mounted three dimensional display," in *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, 1968, pp. 757–764.

[177] T. P. Caudell and D. W. Mizell, "Augmented reality: An application of heads-up display technology to manual manufacturing processes," in *Proceedings of the twenty-fifth Hawaii international conference on system sciences*, 1992, vol. 2, pp. 659–669.

[178] H. Kato and M. Billinghurst, "Marker tracking and HMD calibration for a video-based augmented reality conferencing system," in *Proceedings - 2nd IEEE and ACM International Workshop on Augmented Reality, IWAR 1999*, 1999, pp. 85–94, doi: 10.1109/IWAR.1999.803809.

[179] C. Arth, R. Grasset, L. Gruber, T. Langlotz, A. Mulloni, and D. Wagner, *The History of Mobile Augmented Reality: Developments in Mobile AR Over the Last 50 Years*. 2015.

[180] E. Todeschini, "Augmented-reality signature capture," US9251411B2, 2014.

[181] M. Skarulis, "Systems and methods for an augmented reality platform," US20130016123A1, 2015.

[182] S. J. Henderson and S. Feiner, "Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret," in *Science and Technology Proceedings - IEEE 2009 International Symposium on Mixed and Augmented Reality, ISMAR 2009*, 2009, pp. 135–144, doi: 10.1109/ISMAR.2009.5336486.

[183] 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, doi: 10.1109/TVCG.2010.245.

[184] C. Moro, Z. Štromberga, A. Raikos, and A. Stirling, “The effectiveness of virtual and augmented reality in health sciences and medical anatomy,” *Anat. Sci. Educ.*, vol. 10, no. 6, pp. 549–559, Nov. 2017, doi: 10.1002/ase.1696.

[185] L. Rebenitsch and C. Owen, “Review on cybersickness in applications and visual displays,” *Virtual Real.*, vol. 20, no. 2, pp. 101–125, Jun. 2016, doi: 10.1007/s10055-016-0285-9.

[186] G. A. Koulieris, K. Akşit, M. Stengel, R. K. Mantiuk, K. Mania, and C. Richardt, “Near-Eye Display and Tracking Technologies for Virtual and Augmented Reality,” *Comput. Graph. Forum*, vol. 38, no. 2, pp. 493–519, 2019, doi: 10.1111/cgf.13654.

[187] J. Miller, M. Hoover, and E. Winer, “Overcoming Limitations of the HoloLens For Use in Product Assembly,” *IS&T Int. Symp. Electron. Imaging Sci. Technol.*, pp. 1–9, 2019.

[188] S. Choi, “Apparatus and method for providing haptic augmented reality,” US20100141409A1, 2013.

[189] J. Flaks, “System and method for high-precision 3-dimensional audio for augmented reality,” US20120093320A1, 2014.

[190] E. Kruijff, J. E. Swan, and S. Feiner, “Perceptual issues in augmented reality revisited,” in *9th IEEE International Symposium on Mixed and Augmented Reality 2010: Science and Technology, ISMAR 2010 - Proceedings*, 2010, pp. 3–12, doi: 10.1109/ISMAR.2010.5643530.

[191] Mott et al., “Adaptive fiducials for image match recognition and tracking,” 14/475,333, 2018.

[192] Balanet al., “Passive optical and inertial tracking in slim form-factor,” US20170357333A1, 2018.

[193] Balan et al., “Two-hand interaction with natural user interface,” US20150040040A1, 2016.

[194] Asbun et al., “Gaze-driven augmented reality,” US20160259977A1, 2018.

[195] Swaminathan et al., “Enabling augmented reality using eye gaze tracking,” US20140168056A1, 2018.

[196] W. S. Lee, E. J. Han, and S. Y. Sohn, “Predicting the pattern of technology convergence using big-data technology on large-scale triadic patents,” *Technol. Forecast. Soc. Change*, vol. 100, pp. 317–329, 2015, doi: 10.1016/j.techfore.2015.07.022.

[197] K. H. Weber, *Engineering verfahrenstechnischer Anlagen: Praxishandbuch mit Checklisten und Beispielen*. Springer-Verlag, 2016.

[198] D. Mourtzis, K. Vlachou, F. Xanthi, E. Vlachou, V. Zogopoulos, and X. Fotini, “Integrated Production and Maintenance Scheduling Through Machine Monitoring and Augmented Reality: An Industry 4.0 Approach SEE PROFILE Integrated Production and Maintenance Scheduling Through Machine Monitoring and Augmented Reality: An Industry 4.0 Approach,” *Springer*, vol. 513, pp. 354–362, 2017, doi: 10.1007/978-3-319-66923-6_42.

[199] G. Pintzos, L. Rentzos, N. Papakostas, and G. Chryssolouris, “A novel approach for the combined use of AR goggles and mobile devices as communication tools on the shopfloor,” in *Procedia CIRP*, 2014, vol. 25, no. C, pp. 132–137, doi: 10.1016/j.procir.2014.10.021.

[200] D. Segovia, M. Mendoza, … E. M.-P. C., and undefined 2015, “Augmented reality as a tool for production and quality monitoring,” *Elsevier*.

[201] C. Liu, S. Cao, W. Tse, X. X.-J. of M. Systems, and undefined 2017, “Augmented reality-assisted intelligent window for cyber-physical machine tools,” *Elsevier*.

[202] E. Arroyo, M. Hoernicke, P. Rodr\'\iguez, and A. Fay, “Automatic derivation of qualitative plant simulation models from legacy piping and instrumentation diagrams,”

Comput. Chem. Eng., vol. 92, pp. 112–132, 2016.

[203] W. C. Tan, I.-M. Chen, and H. K. Tan, “Automated identification of components in raster piping and instrumentation diagram with minimal pre-processing,” in *Automation Science and Engineering (CASE), 2016 IEEE International Conference on*, 2016, pp. 1301–1306.

[204] W. C. Tan, I.-M. Chen, S. J. Pan, and H. K. Tan, “Automated design evaluation on layout of Piping and Instrumentation Diagram using Histogram of Connectivity,” in *Automation Science and Engineering (CASE), 2016 IEEE International Conference on*, 2016, pp. 1295–1300.

[205] A. E. Uva, M. Gattullo, V. M. Manghisi, D. Spagnulo, G. L. Cascella, and M. Fiorentino, “Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations,” *Int. J. Adv. Manuf. Technol.*, vol. 94, no. 1–4, pp. 509–521, Jan. 2018, doi: 10.1007/s00170-017-0846-4.

[206] 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, 2010.

[207] 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.

[208] M. Prensky, “Digital natives, digital immigrants part 1,” *Horiz.*, vol. 9, no. 5, pp. 1–6, 2001.

[209] S. Bennett, K. Maton, and L. Kervin, “The ‘digital natives’ debate: A critical review of the evidence,” *Br. J. Educ. Technol.*, vol. 39, no. 5, pp. 775–786, 2008.

[210] B.-W. Lin and D. Berg, “Effects of cultural difference on technology transfer projects: an empirical study of Taiwanese manufacturing companies,” *Int. J. Proj. Manag.*, vol. 19, no. 5, pp. 287–293, 2001.

[211] S. Kim, M. A. Nussbaum, and J. L. Gabbard, “Augmented reality ‘smart glasses’ in the

workplace: industry perspectives and challenges for worker safety and health," *IIE Trans. Occup. Ergon. Hum. factors*, vol. 4, no. 4, pp. 253–258, 2016.

[212] J. L. Gabbard, J. E. Swan, and D. Hix, "The effects of text drawing styles, background textures, and natural lighting on text legibility in outdoor augmented reality," *Presence Teleoperators Virtual Environ.*, vol. 15, no. 1, pp. 16–32, 2006.

[213] J. L. Gabbard, J. E. Swan, D. Hix, S.-J. Kim, and G. Fitch, "Active text drawing styles for outdoor augmented reality: A user-based study and design implications," in *Virtual Reality Conference, 2007. VR'07. IEEE*, 2007, pp. 35–42.

[214] K.-H. Seok and Y. S. Kim, "A study on providing prompt assembly information using AR manual," in *Convergence and Hybrid Information Technology, 2008. ICCIT'08. Third International Conference on*, 2008, vol. 1, pp. 693–695.

[215] M. Sette, L. Tao, and N. Jiang, "A Knowledge-Driven Web Tutoring System Framework for Adaptive and Assessment-Driven Open-Source Learning," in *Computer Software and Applications Conference (COMPSAC), 2017 IEEE 41st Annual*, 2017, vol. 2, pp. 712–717.

[216] S. Oh, W. Woo, and others, "CAMAR: Context-aware mobile augmented reality in smart space," in *Proceedings of International Workshop on Ubiquitous Virtual Reality*, 2009, pp. 15–18.

[217] 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.

[218] J. Grubert, T. Langlotz, S. Zollmann, and H. Regenbrecht, "Towards pervasive augmented reality: Context-awareness in augmented reality," *IEEE Trans. Vis. Comput. Graph.*, vol. 23, no. 6, pp. 1706–1724, 2017.

[219] R. Hervás, J. Bravo, J. Fontecha, and V. Villarreal, "Achieving adaptive augmented reality through ontological context-awareness applied to aal scenarios," *J. Univers. Comput. Sci.*, vol. 19, no. 9, pp. 1334–1349, 2013.

[220] J. Zhu, S. K. Ong, and A. Y. C. Nee, “An authorable context-aware augmented reality system to assist the maintenance technicians,” pp. 1699–1714, 2013, doi: 10.1007/s00170-012-4451-2.

[221] S. J. Henderson and S. Feiner, “Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret,” in *2009 8th IEEE International Symposium on Mixed and Augmented Reality(ISMAR)*, 2009, vol. 00, pp. 135–144, doi: 10.1109/ISMAR.2009.5336486.

[222] M. Ruta, F. Scioscia, S. Ieva, D. De Filippis, and E. Di Sciascio, “Indoor/outdoor mobile navigation via knowledge-based POI discovery in augmented reality,” in *Web Intelligence and Intelligent Agent Technology (WI-IAT), 2015 IEEE/WIC/ACM International Conference on*, 2015, vol. 3, pp. 26–30.

[223] S. Akbarinasaji and E. Homayounvala, “A novel context-aware augmented reality framework for maintenance systems,” *J. Ambient Intell. Smart Environ.*, vol. 9, no. 3, pp. 315–327, 2017, doi: 10.3233/AIS-170435.

[224] H. Flatt, N. Koch, C. Röcker, A. Günter, and J. Jasperneite, “A context-aware assistance system for maintenance applications in smart factories based on augmented reality and indoor localization,” in *Emerging Technologies & Factory Automation (ETFA), 2015 IEEE 20th Conference on*, 2015, pp. 1–4.

[225] “Protégé, https://protege.stanford.edu/ last accessed (June, 4, 2018).” 2018.

[226] F. Scioscia *et al.*, “A mobile matchmaker for the Ubiquitous Semantic Web,” *Int. J. Semant. Web Inf. Syst.*, vol. 10, no. 4, pp. 77–100, 2014.

[227] “AnTuTu Benchmark, https://antutu.com/en/ last accessed (July, 9, 2018).” 2018.

[228] “oManual: The Open Manual Forma, http://www.omanual.org/ last accessed (June, 11, 2019).” 2019.

[229] “dita.xml.org, https://dita.xml.org/ last accessed (June, 11, 2019).” 2019.

[230] “DocBook.org, https://docbook.org/ last accessed (June, 11, 2019).” 2019.

[231] “IEEE-SA - Standards & Projects Most Relevant To Augmented Reality, https://standards.ieee.org/initiatives/ar/stds.html/ last accessed (June, 11, 2019).” 2019.