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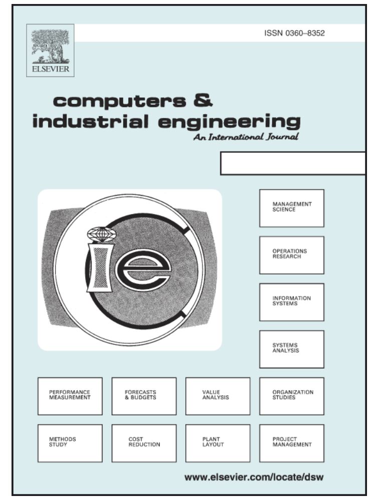

A Survey of Industrial Augmented Reality

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ABSTRACT

This article aims to evaluate the impact of Augmented Reality (AR) applicability and usefulness on real industrial processes by employing a systematic literature review (SLR). The SLR was performed in five digital libraries to identify articles and reviews concerning the AR applicability from 2012 to 2018. A patent search in Google's patents database was also conducted, for the same period. This paper describes how AR has been applied, which industries are most interested in the technology, how the technology has been developed to meet industry needs, as well as the benefits and challenges of AR. This survey concludes by providing a starting point for companies interested in integrating AR into their processes and proposing future directions for AR developers and researchers.

1. Introduction

The fourth industrial revolution is challenging industries to change their business from a seller's into a buyer's market. This implies that products and processes have to be personalized according to customer needs, delivered in a short period meet similar costs as seen in a mass production (Ciortea et al., 2018). To achieve expected results, industries are investing in new technologies that increase manufacturing flexibility and reduce decision-making procedures (Motyl et al., 2017; Lasi et al., 2014).

One of the leading technologies in this context is Augmented Reality (AR), which can be applied in different fields, such as medicine, education, architecture, marketing, maintenance and assembly process (Billinghurst et al., 2015; Chatzopoulos et al., 2017).

In industrial operations, AR has been presented as a powerful tool to improve flexibility and process efficiency (Fraga-Lamas et al., 2018). Although many studies have confirmed the benefits of AR in various industries, its real use is still not recurrent (Palmarini et al., 2018).

This paper aimed to identify the reasons why AR technology is still not present in most industries and consequently reduce the gap between AR developers and users by presenting industrial needs, proposing visualization device tendencies and discussing existing development frameworks. Additionally, the study ought to identify new AR developments and the technology limitations. To achieve the proposed objectives, a systematic literature review (SLR) was conducted. Contrasting from most published SLR concerning AR, the present paper will analyze patents.

The rest of this paper is structured as follows: Section 2 defines and classifies AR according to previous publications. Section 3 presents previous reviews concerning AR for industrial operations. Section 4 is divided into two subsections: the first one describes the method applied to conduct the SLR the second one details the method to identify patents. Section 5 compiles all data obtained from the survey and answers the research questions formulated in Section 3. Finally, Section 6 presents some final considerations and proposes future trends to AR developers with the goal of meeting users' needs and informing users of the pros and cons of AR use nowadays.

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2. AR definition

AR is a variation of Virtual Reality (VR), where virtual objects are superimposed on the real environment (Azuma, 1997), which must attend to three requirements: combine virtual and real objects in a real environment, run interactively and in real time register real and virtual objects with each other. In other words, AR should register or correct alignment of the virtual world with real one (Azuma et al., 2001). On one hand, VR technology creates a virtual environment presented to our senses in such a way that we experience it as if we were really there. Conversely, AR refers to the incorporation of virtual objects into a real three-dimensional scene.

To ensure consistent overlapping of objects, AR systems must estimate, in real time, the virtual object position and orientation (Lima et al., 2017). One of the most usual methods to realize such an estimate is by using markers in the real scene. These markers will be identified by cameras and compared with patterns previously defined (Khan et al., 2015). However, in some cases, the use of markers is not feasible, and other tracking methods, that are generally more complex and less mature, have to be applied (Lima et al., 2017). Some commonly adopted markerless tracking methods, are Natural Feature Tracking (NFT) Simultaneous Localization and Mapping (SLAM).

- In NFT techniques, some characteristic points from the image are detected in real-time by the AR system and the virtual objects pose are calculated based on these points (Fraga-Lamas et al., 2018).

- The SLAM algorithms were first developed for robotics application to estimate real-time positions and orientations of the robot and then adapted for AR (Billinghurst et al., 2015). This method consists of constructing a probabilistic feature-based map that estimates the real-time pose of camera and position of interested features (Davison et al., 2007). The location of feature points are used to create 3D point clouds for the unknown environment in real time, and then determine the system navigation paths as a pre-scanning process. The 3D point cloud tracking increased after commercial sensors became capable of detecting environment structure information, by using technologies such as structured light, wireless dosimeters, and X-ray propagation (Billinghurst et al., 2015; Loy Rodas and Padoy, 2015). Once these sensors can reconstruct a 3D object, the object is compared to a known model to estimate the virtual object pose (Bae et al., 2016). One method of implementing SLAM is via Parallel Tracking and Mapping (PTAM), developed for AR, where tracking and mapping occur separately. PTAM makes it possible to use a robust tracking method, execute both tasks in different processing core reduce video frame mapping in frames where the camera moved (Klein and Murray, 2007).

AR techniques can be classified according to devices being utilized (Azuma et al., 2001). Three main categories are proposed for its classification:

- Using head mounted displays (HMD), wearable hardware, such as goggles or helmets. These devices are categorized into two forms: optical see-through and video see-through (Azuma, 1997). In optical see-through systems, a half-transparent mirror is responsible for allowing users to see the real world and reflecting the information into the user's eyes, combining the real and virtual objects (Nishihara, 2015). In video see-through systems the real world is previously digitized, generally by an attached camera the world and digital information are merged before being shown as an opaque display (Azuma et al., 2001; Nishihara, 2015).
- Using mobile screens, such as smartphones and tablets, or fixed ones, such as monitors, to display virtual objects. In these systems, a coupled camera is responsible for capturing the real world, while a device, or a connected computer, renders the virtual image and projects it onto the equipment screen (Nishihara, 2015).
- Using Spatial Augmented Reality (SAR). These systems utilize projectors to project the virtual information directly onto the real objects (Azuma et al., 2001), allowing user interaction with the virtual object.

3. Related Works

To identify reviews concerning AR application on industrial environments previously, a search in ACM, IEEE Xplore, Scopus, Science Direct and Springer Link libraries was performed in December 2018. These five digital libraries were employed because they cover most of the computer sciences and industrial engineer journals. A total of 11 reviews were found, which focused on AR hardware and techniques, or a specific industrial domain.

In 2012 and 2013, Nee et al. (2012) and Nee and Ong (2013) respectively published reviews concerning applications of AR and VR in manufacturing. In their work, they identified hardware devices, tracking products haptic devices available in that year and researched literature on the main usages of AR in manufacturing. This work listed applications in design, robotics, layout planning, maintenance, CNC simulation, as well as operational training. All applications have their systems described, concerning hardware and system. The study concluded that the accuracy required in tracking and registration in such applications are the main limitations to its applicability in manufacturing. However, the conclusions in these papers, both pointed out main uses of AR and VR technology, but didn't present their research protocol.

In 2013, Rankohi and Waugh (2013) focused their review on the construction industry. With a structured research method, they identified 133 relevant papers from 1999 to 2012 in architecture, engineering, construction facility management. They identified the origin of the studies, research methods, project phase, target audience, comparison role and facilities. As a conclusion, this review suggested that a future trend should be Internet-based mobile AR systems for use in construction and maintenance phases.

In 2016, Wang et al. (2016) published an overview of the technical features, characteristics the broad range of applications of AR assembly systems. This work identified, from 1990 to 2015, 91 relevant publications concerning AR for assembly operations, which were divided into assembly guidance, training, process simulation planning. By that time, the main issues identified in this domain was tracking and registration, collaborative interfaces, 3D workspace scene capture, as well as knowledge representation and context-aware assembly systems.

Furthermore, in 2016, Elia et al. (2016) published a revision analyzing the application of AR systems in manufacturing from 2007 to 2016. Based on this research, they evaluated hand-held devices (HHD), projectors, haptic devices force feedback and head-mounted displays (HMD) according to their reliability, responsiveness agility in manufacturing.

Another review evaluating devices was published in 2017. Syberfeldt et al. (2017) analyzed commercial HMD and evaluated them according to their weight, field of view, battery life, optics, camera, open API, audio, controls, processors, storage, memory connectivity. The proposal technique tried to simplify the hardware decision for manufacturing purposes and suggest future HMD developments.

In 2017, Büttner et al. (2017) studied AR and VR applications for assistive environments in manufacturing. This paper identified that the main focus of published work is in production using projectors and HMD, followed by maintenance and training, using exclusively HMD. This study identified not only opportunities to develop applications to improve user's learnability and quality but also challenges to improve devices usability by reducing their weight and improving their autonomy.

In a more recent study, Fraga-Lamas et al. (2018) reviewed AR systems focused shipyard. This paper identified many applications, such as quality control, assistance in the manufacturing process, visualization of the location of products and tools, management of warehouses, predictive maintenance using data mining, augmented communication, visualization of installations in hidden areas and remote operation of IIoT and smart connected products and devices. Unlike previous publications, this review also investigated how applications were developed, highlighting the most relevant AR SDKs.

Also published in the first half of 2018, Fast-berglund et al. (2018) proposed a case study with 220 participants to test and validate Extended Reality (ER) technologies in manufacturing. In this case study, they concluded that limitations in hardware and application design are the leading cause of underutilization technology in manufacturing.

In the second half of 2018, Damiani et al. (2018) evaluated the current state of AR and VR and their practical application in industrial systems. In this study, they considered that the technology has been applied in product design, logistics, production system management and safety maintenance.

Finally, in 2018, Segura et al. (2018) analyzed Visual Computing technologies as a critical role in operators' empowering process. They pointed out that AR has real practical uses in Human-Machine Interaction; however, some markerless applications that require robust tracking are still limited to test environments.

4. Research Methodology

4.1. Systematic Literature Review

The research methodology to conduct the SLR was adopted from guidelines proposed by Budgen and Brereton (2006). According to their guidelines, a SLR process is composed of three main phases:

- The planning phase: in this phase, authors need to define the research questions and define the basic review procedures (review protocol).
- Conducting phase: after planning the review procedures, this phase is responsible for identifying previously conducted research, select primary studies, evaluate the quality of studies (quality assessment), as well as extract and synthesize data.
- Reporting phase: in this phase, authors define their communications strategy and publish it in journals or magazines, conferences, web pages, or other suitable communication channels.

4.1.1. SLR Planning Phase

The purpose of this SLR is to analyze how and where AR has been applied in an industrial context. Additionally, another goal is to understand how the application has been developed and learn about its gains and challenges. Thus, this work intends to answer the research questions described in Table 1.

After analyzing all the related works, it was possible to identify that any of them answered the posed review questions because they are focused on a specific manufacturing process, segment, or hardware. Nevertheless, they could be used as a framework for more comprehensive research on the manufacturing process.

4.1.1.1. Search Strategy

To define the search strings, a combination of the technology name (Augmented Reality) and application place (manufacturing, production assembly) was tested. This test was conducted on the same basis as other previously researched SLR. After this search, some other keywords were presented in relevant papers. These keywords were also incorporated as a search string. The search strings used in this work are listed in Table 2:

Titles and abstracts were searched for the previously mentioned strings, except for Springer Link where only titles were concerned as this database does not allow abstract searches. The results were filtered to select only articles published in journals.

The conducting of our review protocol followed the PICOC (Population, Intervention, Comparison, Outcome, Context) criteria, as suggested by Budgen and Brereton (2006) and applied by Vilela et al. (2017).

- Population: peer-reviewed publications concerning AR application on production environments.
- Intervention: collect evidence of AR used in activities on the production line.
- Comparison: it does not apply.
- Outcomes: industry segment where AR was used, tools necessary to develop the solution, environment conditions, hardware needed, benefits difficulties for the implementation.
- Context: usage in production environment.

StArt (State of the Art through Systematic Reviews) tool is a software that supports researchers who conduct SLR by applying defined steps, according to a previously elaborated protocol (LaPES, 2018). This tool was adopted to fill the protocol and support the SLR, due to its favorable result reported by Hernandes (2012); Vilela et al. (2017).

4.1.1.2. Inclusion and exclusion criteria

To develop this study, only research articles that were written in English and published from 2012 to 2018 were considered. Based on previous reviews, this period was considered the most relevant to indicate tendencies. Application studies and reviews concerning AR in the production environment were also considered. All applications that considered production environments as the secondary purpose was excluded. Also excluded were short papers (less than five pages), studies irrelevant to the research (considering research questions), non-academic publications (commercial literature, reports posters) and duplicated studies

Table 1
Research questions and motivations for the systematic review.

Research Question	Motivation
RQ1: What is the primary purpose of AR in industrial environments?	This question aims to identify how the technology has been used to daily activities on industrial context.
RQ2: Which kind of industry has developed AR for their production process?	This question intends to identify if the technology is associated with high-value products and complex processes.
RQ3: How AR applications have been developed for production environments?	This question maps the main devices adopted to visualize virtual objects, AR SDK and programming languages used to develop the applications.
RQ4: Which are the leading technology benefits?	This question intends to analyze benefits after the technology implementation for the process described on RQ1.
RQ5: Which are the main challenges to apply AR in production environments?	This question aims to understand the low usability in industries and propose future developments.

Table 2
Search Strings

#	Search String
1	"Augmented Reality" AND "Manufacturing"
2	"Augmented Reality" AND "Production"
3	"Augmented Reality" AND "Assembly"
4	"Augmented Reality" AND "Shop floor"
5	"Augmented Reality" AND "Factory floor"
6	"Mixed Reality" AND "Manufacturing"
7	"Mixed Reality" AND "Production"
8	"Mixed Reality" AND "Assembly"
9	"Mixed Reality" AND "Shop floor"
10	"Mixed Reality" AND "Factory floor"

Table 3
Research questions and extracted information

Research Question	Extracted information
RQ1: What is the primary purpose of AR in industrial environments?	- Application purpose - Ergonomics considerations - Virtual object quality considerations
RQ2: Which kind of industry has developed AR for their production process?	- Industrial segment - Application tests - Application implementation on production environment
RQ3: How AR applications have been developed for production environments?	- Camera configuration - Processing device - Utilized display - Tracking method - AR library and SDKs
RQ4: Which are the leading technology benefits?	- Cited benefits
RQ5: Which are the main challenges to apply Augmented Reality in production environments?	- Cited constraints and challenges

4.1.1.3. Selection procedure

Initially, the studies were extracted from previously listed five library databases, using search result from Table 2, a total of 920 papers were found. However, 307 of these articles appeared in more than one search string and were considered duplicate studies. Removing the duplicated papers, 613 publication abstracts were analyzed to identify if they were an AR industrial application and if they answered at least one of the research questions. After this analysis, 120 works were selected for data extraction in this SLR. Figure 1 illustrates this selection procedure Figure 2 identifies the reason why the papers were rejected, according to the inclusion and exclusion criteria.

4.1.2. Conducting phase

4.1.2.1. Data extraction

Once papers are selected, the next step was to read the full work to extract the information which answers the questions in the present study. Table 3 details the extracted information according to the research questions.

A digital form to record the information of the 94 primary studies was prepared. StArt tool was also adopted in this phase to compile all the information.

4.1.2.2. Quality assessment

The quality assessment helps the reviewer offer guidance on the selected studies, finding an interpretation, minimizing bias maximizing validity (Vilela et al., 2017).

In this study, the quality assessment was utilized to identify subsets of the primary studies. The quality differences are associated with different primary study outcomes. The quality data was collected during the main data extraction.

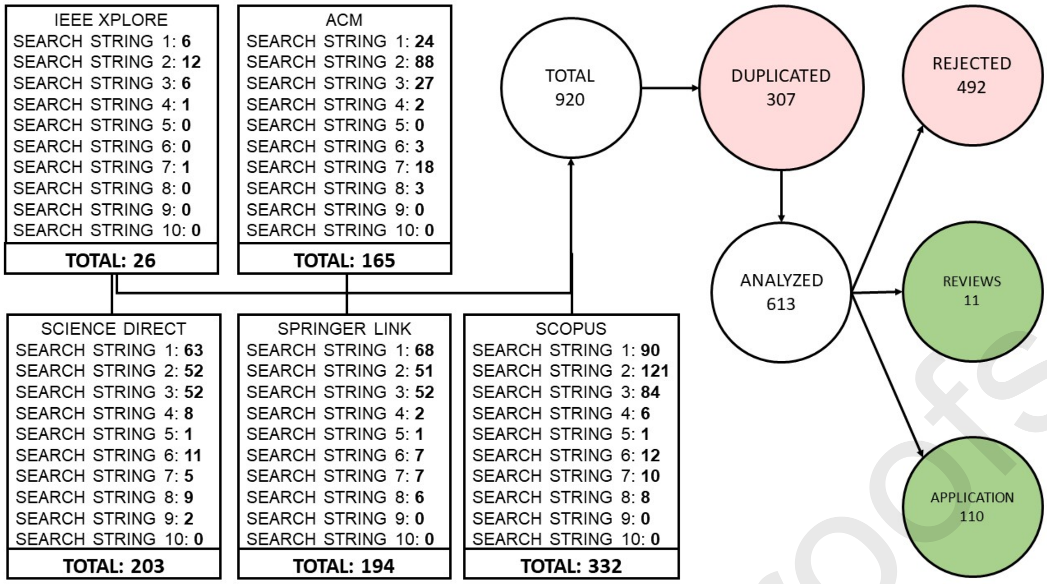

Figure 1: Selection procedure to define primary studies.

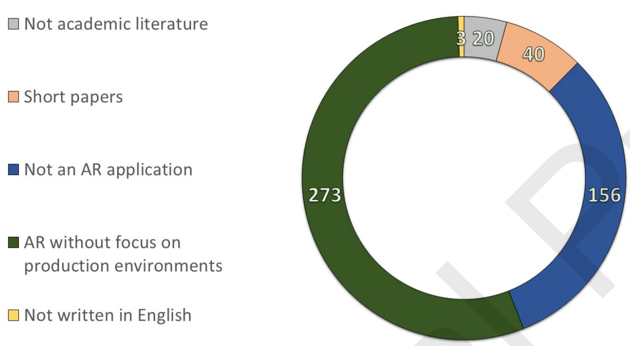

Figure 2: Numbers of excluded papers per rejection causes.

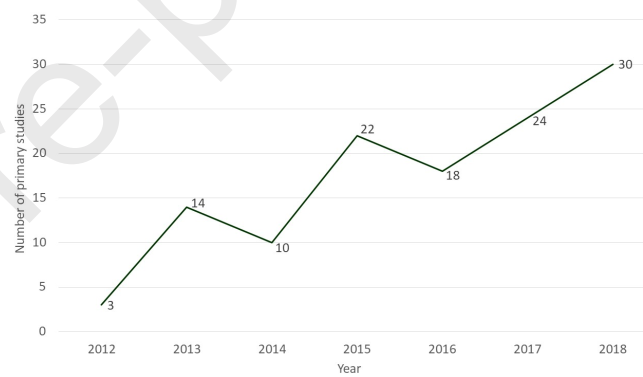

Figure 3: Distribution of primary industrial AR studies selected per year.

The primary study quality assessment was achieved by evaluating credibility, completeness relevance. Twelve quality criteria, adapted from (Vilela et al., 2017; Budgen and Brereton, 2006) were noted with a yes if the criterion was clearly described in the text, partially, if the criterion was not clearly or not thoroughly explored no, if the criterion was not cited. Table 4 lists the criteria evaluation results.

4.2. Patents analysis

To execute the patent analysis, the same strings from the SLR were employed. The search was conducted in Google's patent database, as this search engine can look for patents in more than 17 patent offices and translate them to English. The extracted granted patents were from 2012 to 2018 with the search strings in any part of the text.

A total of 83 patents were identified during the research. Their content was analyzed to judge whether or not the projects are intended for an industrial purpose and if they can answer any SLR research questions. From all identified patents, 38 were considered not relevant because they were not developed for industrial applications or they were not an AR project. Additionally, 29 were identified as visualization devices that could be adopted in an industrial context, but they were presented general context. Finally 16 were considered a combination of hardware and software to be applied in any industrial activity.

5. Results and Discussion

5.1. Bibliometry

A total of 121 studies discuss AR in a production environment, which are applications implementations or reviews. As expected, the publication number has increased in the last seven years, as shown in Figure 3.

Comparing the origin of the studies, 63% of the publications were developed in Europe, followed by 22% from Asia, 10% from North and Central America 5% from Oceania. When considering patents, the most representative continent was Asia with 75% of identified patents, followed by

Table 4
Quality assessment (adapted from Vilela et al. (2017); Budgen and Brereton (2006))

Quality assessment question	Yes	Partially	No
QQ1: Is there a clear statement of the goals of the research? (Vilela et al., 2017)	114	6	1
QQ2: Is the proposed technique clearly described? (Vilela et al., 2017)	67	37	17
QQ3: Is there an adequate description of the context (industry, laboratory setting, products used and so on) in which the research was carried out? (Vilela et al., 2017)	90	25	6
QQ4: Was the data collection well carried out? (Budgen and Brereton, 2006)	78	37	6
QQ5: Was the data analysis sufficiently rigorous? (Vilela et al., 2017)	66	44	9
QQ6: Are the findings credible? (Budgen and Brereton, 2006)	100	20	1
QQ7: Is there a discussion about the results of the study? (Budgen and Brereton, 2006)	76	41	4
QQ8: Are the limitations of this study explicitly discussed? (Vilela et al., 2017)	56	20	45
QQ9: Are the lessons learned interesting? (Vilela et al., 2017)	83	37	1
QQ10: Is the article relevant for practitioners? (Vilela et al., 2017)	103	16	2
QQ11: Is there sufficient discussion of related work? (Vilela et al., 2017)	66	40	15
QQ12: Are links between data, interpretation and conclusions clear? (Budgen and Brereton, 2006)	104	13	4

Figure 4: Distribution of industrial AR patents and primary studies per continent.

North America with 17%.

No primary studies or patents were found to originate from Africa and South America. The country that most published about this review subject was Germany with 18 primary studies, followed by Italy with 15, Singapore with 14 and Sweden with 13. When considering patents, China has the highest number, with 29, followed by the United States, with 8. Figure 4 illustrates the number of primary studies and patents per continent.

Considering sponsorship organization categories (public, public-private partnership, private), 45% of primary studies did not mention any sponsorship, 37% declared a public organization source as sponsorship, 10% as a private organization sponsorship 8% as a public-private partnership. Figure 5 shows the number of primary studies per continent and the corresponding sponsorship category. None of the cases were declared as a private organization sponsorship with funds, but provided infrastructure and resources (hardware and software). Considering cited public institutions, the most cited was the European Commission with seven works from the Horizon 2020 research project and four from the Know4Car Project. It is also remarkable and worth noting that the Ministry of Education, Science, Research Sport of the Slovak Republic contributed to three publications.

5.2. RQ1: What is the primary purpose of AR in industrial environments?

To answer the first research question, only primary AR studies with an ongoing application were considered. Therefore, this analysis was conducted with 110 papers. The AR development applicability was grouped into 10 categories: manual assembly, robot programming and operations, maintenance, process monitoring, training, process simulation, quality inspection, picking process, operational setup ergonomics and safety. Around 11% of the selected works had applications in more than one group. Moreover, the most cited com-

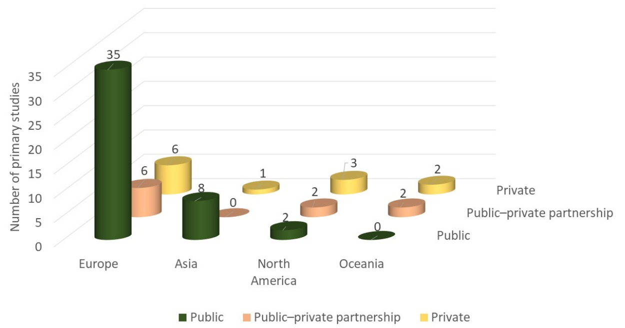

Figure 5: Primary industrial AR studies per continent and sponsorship category.

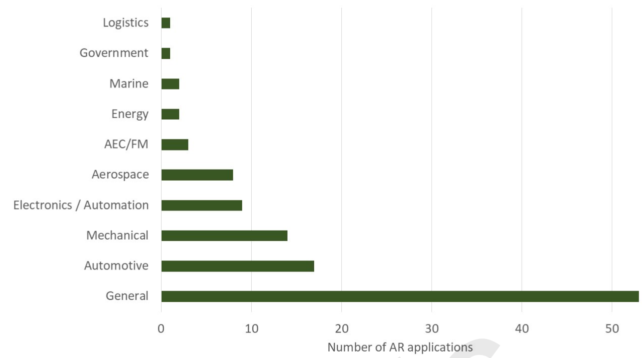

Figure 7: Distribution of industrial AR applications per industrial segments.

Figure 6: Distribution of the industrial applicability of the primary industrial AR studies.

binations are picking process with manual assembly or operational setup, as reported by Terhoeven et al. (2018); Funk et al. (2017) manual assembly with simultaneous quality inspection, as proposed by Liu et al. (2014); Yi et al. (2015). Figure 6 shows the number of primary studies per applicability category.

The majority of AR applications in industrial environments are focused on manual assembly processes by providing work instructions to the users on how to execute an activity. These instructions are also presented in maintenance and training activities, quality inspections, machining setups logistics processes, such as picking. Two process innovations can be highlighted for these applications. Firstly, the creation of solutions that can adapt themselves according to the user experience. Secondly, the use of remote assistance with AR that reduces the need of having experts on-site and, consequently, cost and time. These applications are also responsible for 69% of AR patents in the industrial context, which suggests a high level of innovation potential.

AR also has been applied to improve users' safety in situations that demand human-robot interaction. These applications focus on creating a visible robot movement path that shows during the programming phase where are the accident risk areas. Some other implementations focused on users, showing them, during the operation, where the risk areas are located.

Finally, some works focus on processing information by proposing visual management using AR. This kind of application proposes a quick analysis and decision making on-site where the process occurs.

Ergonomics was also an aspect evaluated during this review, comprising 12% of the primary studies discussed this topic. Two main issues were argued. First, HMD weight, latency limited field of view, that according to some studies could cause headaches, dizziness nausea in some users. The second point was concerning user's mobility when using hand-held displays. No studies presented legal aspects of AR use in real production environments or cited studies concerning occupational diseases.

We also analyzed whether primary study authors considered virtual object quality as relevant for the application purpose. Their quality was discussed in two categories, accuracy and sharpness. Accuracy was argued in 40% of the studies to be an essential feature in the application, while sharpness in 23%. None of the studies measured the virtual object pose error or evaluated its form and color in comparison with the real reference.

5.3. RQ2: Which kind of industry has developed AR for their production process?

It was identified that a considerable number of developed applications were not focused on a specific industry, but were general applications for industrial issues present in many segments. This fact is explained when the research sponsorship was analyzed. It is remarkable that most researches were conducted by using public resources.

From works that declare a implementation context, nine industrial segments were identified: architecture, engineering, construction and facilities management (AEC/FM), aeronautics, automotive, electronics / automation, energy, government, logistics, marine and mechanical. These segments represent 52% of developed solutions. The remaining 48% were applications not developed for a specific segment, named as a general segment. Figure 7 presents the complete breakdown of AR applications per industrial segment.

From all of the studied AR applications, 97% were tested to ensure their viability and compare AR pros and cons with traditional processes. However, just 5% of them were im-

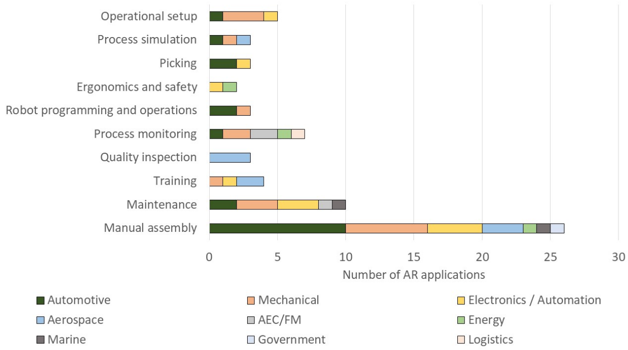

Figure 8: Industrial AR applications per industrial segment and applicability category.

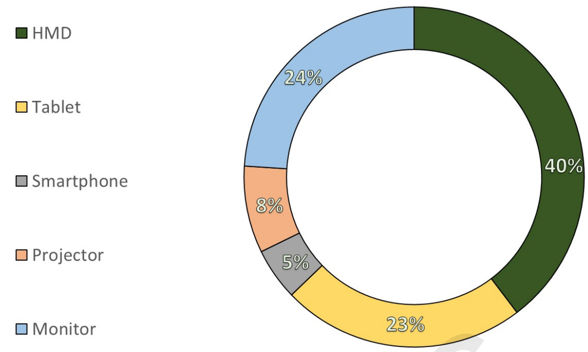

Figure 9: Percentage of industrial AR applications per visualization devices.

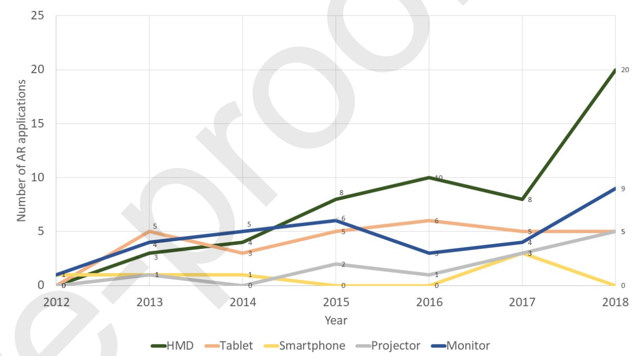

Figure 10: Industrial AR applications per visualization devices and year.

plemented in a production environment, which confirms the same scenario described by Palmarini et al. (2018).

None of the privately sponsored works, identified in primary studies, declared that the technology was installed in their production system. The only implemented case with a private organization sponsorship results from a public-private partnership from Doshi et al. (2017). Considering these numbers, it was concluded that industries are not focusing on developing specifics applications to solve their problems, but they are interested in finding standard applications for adaptation to their production scenario.

Excluding the General segment applications, link between industrial segment and applicability category was evaluated. This relationship is an important cue to understand some sector's needs, identify applications not previously explored in some segments, and consequently, propose future researches (Figure 8).

After analyzing the studies that specified an industrial segment, it was noted that these technology investments are not associated with final product cost, but are instead associated with manufacturing activity complexity. This fact is notable by the use of AR in many general mechanical industries, which generally produce small components for other companies. The segment that stood out the most was automotive. This industrial sector developed applications for many purposes, not focusing exclusively on working instructions. This demand can be explained as an effort to improve production flexibility, as the main characteristic of this industry is production in line, and most of them offer many different optional items for customers.

5.4. RQ3: How AR applications have been developed for production environments?

Considering hardware, applications with fixed and mobile displays have been identified. For 25% of the implementations, the processing and display are performed on different devices, whereas, this mainly occurs because many implementations render in a fixed computer and synchronize the real and virtual objects in a mobile device. This sort of application is notable in remote assistance with AR, where two or more users interact at the same time.

Through analysis of visualization devices, four applications were identified that did not mention which device was utilized. On the other hand, ten applications used more than one hardware to validate their implementation (Figure 9).

HMDs have the most significant use in the analyzed period. According to Figure 10, their use has significantly increased in production environments in the last five years, with 2018 responsible for almost 54% of the AR applications. The same tendency was identified in patent analysis. From 29 identified devices' patents, 86% included HMD projects. The other 14% are equally divided into hand-held devices (tablets or smartphones) and projector-based projects. Their usability indicates that for industrial environments, it is essential to give operators the freedom to execute all required movements to do their tasks.

Seven different HMDs were employed in primary study applications. Most of them are optical see-through (OST), and some of video see-through (VST) are devices for VR that were adapted to AR applications. For example, Oculus Rift that was adapted by Peppoloni et al. (2015); Syberfeldt et al. (2015, 2016); Gonzalez-Franco et al. (2017); Brizzi et al. (2018). From identified HMDs, just three are currently commercially available, which suggests that this hardware technology is still in early stage of evolution. An example of this evolution can be observed in device display resolution, typically found to be 1268x720 pixel, while cameras can accomplish resolution of up to 1920x1080 pixels with

Table 5
AR used HMDs.

Product name	Optics	Display resolution (pixels)	Camera resolution (pixels)	Sensors	Frame rate	DFOV	Weight	Operating system	Commercial status
Laster Wave	OST	Not found	1280x720 30 fps	3 DOF: gyroscope magnetometer accelerometer	Not found	21°	100g	Android iOS	Discontinued
Microsoft Hololens	OST	1268x720	1280x720 30 fps	3 DOF: gyroscope magnetometer accelerometer Depth-sensing cameras	60 fps	45°	600g	Windows	Available
Oculus Rift DK2s	VST	1268x720	1920X1080 60 fps	3 DOF: gyroscope magnetometer accelerometer	75 fps	100°	380g	Windows	Available
Penny C Wear	OST	853x480	Not found	Motion tracking	Not found	47°	65g	Windows Linux	Discontinued
VUZIX iWear WRA 920AR	VST	640 x 480	640 x 480 30 fps	3 DOF: gyroscope magnetometer accelerometer	60 fps	31°	85g	Windows MAC	Discontinued
VUZIX M 100	OST	240x400	1920 X 1080 60 fps	3 DOF: gyroscope magnetometer accelerometer Ambient light GPS Proximity	60 fps	15°	150g	Android iOS	Available
VUZIX Star 1200 XL	OST	852 x 480	1920 X 1080 60 fps	3 DOF: gyroscope magnetometer accelerometer	60 fps	35°	250g	Windows OSX Linux	Discontinued

60 fps.

All identified HMDs, cited in the analyzed publications or patents, have a gyroscope, a magnetometer and a accelerometer for capturing its pose and movements. The main innovative HMD was Microsoft Hololens which offers users a depth-sensing camera that scans the environment, leading to more efficient tracking.

However, improvement in sensors and cameras has increased devices weight. All HMD that are still commercially available, and new developments, weigh at least 150g their diagonal field of view (DFOV) is lower than 100°. Table 5 shows used commercial HMD and their technical features.

Another relevant consideration while implementing AR is the selected tracking method. Identified tracking methods were classified as follows: 2D recognition (wherein an environment bi-dimensional feature is used for identification), 3D recognition (wherein a three-dimensional environment feature is used for identification), location-based, marker-based (wherein a feature is included in the environment for identification) sensor-based. Despite being considered one of the main points in AR systems, 11% of selected studies did not declare the employed tracking method. Figure 11 shows the percentage found for each method.

When comparing the primary purpose of the AR with the tracking method utilized (Figure 12), activities that do not need high mental workload or demand just a priori knowledge, such as picking or part of quality inspections that required just a visual comparison with a preset standard to identify if some component is missing, presented low utilization of 3D recognition methods. Furthermore, the complexity of using sensor-based tracking is also evident as its application was used just for robot programming and opera-

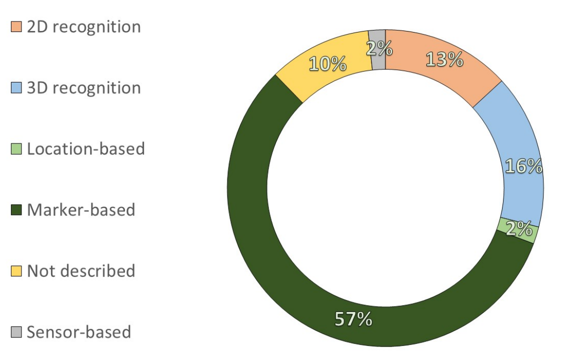

Figure 11: Percentage of industrial AR tracking methods in the industrial applications.

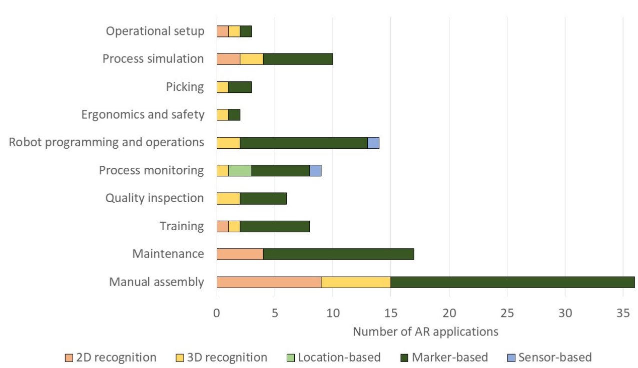

Figure 12: Industrial AR applications per tracking method and applicability category.

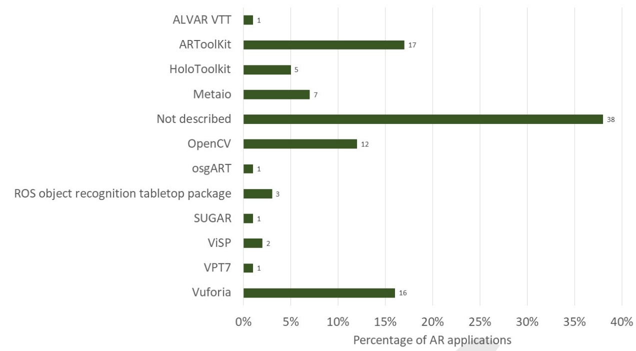

Figure 13: Number of industrial AR development tools.

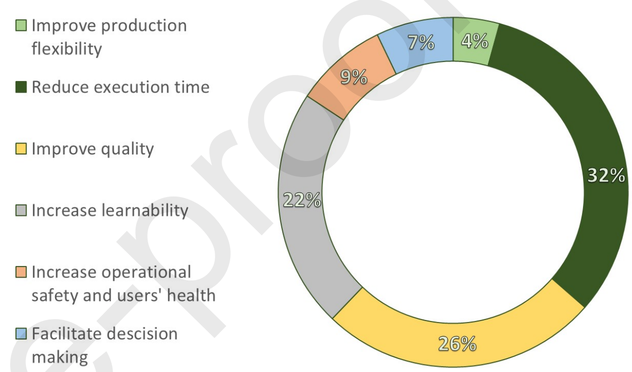

Figure 14: Percentage of main benefits of industrial AR use on production environment.

tions and process monitoring, applications where sensors are already part of the process and are adapted to source also the AR implementation.

As a tendency in future developments, 2D recognition has proven to have techniques which ensure its usability in real scenarios. The use of natural objects, available in the real scene, can be a low-cost solution to eliminate markers and lead to a good result for the virtual object, even with the reference image partially covered.

For software development, it was found that 63% of applications declared the use of an AR framework. All identified frameworks during the SLR execution were listed in Table 6 and their use percentage represented in Figure 13. None of the primary studies or patents described any framework focus on industrial AR development.

All implementations run on Android, iOS, or the Windows platform. Some projects were open-source or provides free license options. Unity 3D and Vuforia, one of the most popular AR SDKs, were responsible for most of the developments. The choice in platform can be justified by the capability that it has to generate markers, with different characteristics, that are suitable for Vuforia's recognition mechanism (Blanco-Novoa et al., 2018). OpenCV libraries also have been widely adopted for applications development. This library not only offers a possible way of interfacing with Kinect camera but also provides facial tracing function. Most of the applications using OpenCV were created via Blender.

5.5. RQ4: Which are the leading technology benefits?

Analyzing primary studies, it was possible to identify, that 90% of them, converge to 6 main benefits, as shown in Figure 14. All papers cited more than just one benefit after analysis.

According to primary studies, operational time decrease, production flexibility improvement, production quality learnability increase are factors that contribute to costs reduction. Even with this analysis, no study calculated this reduction percentage compared to the traditional process.

Applications that involved human-robot interactions reported user safety results. In these cases, analyzing robot movements in a real scenario make it easier for robot programmers to design the best robot path, avoiding collisions. Also, these applications show operators the location of unsafe areas.

Health, as a benefit, was reported due to operator's mental workload reduction. As activities are more natural in a real environment, users do not need to interpret drawings or data.

Some studies have identified that having process data locally available could accelerate decision-making; however, this benefit has not been explored in production environments.

Table 6
AR development framework.

Product	License	Platforms	Characteristics	Status
ALVAR VTT	Free Commercial	Android iOS Flash	Marker NFT	Available
ARToolKit	Open source Commercial	Android iOS Windows	Marker NFT	Available
HoloToolkit	Free	Windows	Marker NFT Spacial mapping	Available
Metaio	Free Commercial	Android iOS Windows	Marker Picture Marker Tracking Image Tracking Instant(snapshot) Tracking 3D SLAM Tracking CAD based 3D Tracking Face Tracking	Discontinued
OpenCV	Open source	Windows Linux Mac OS iOS Android	Marker NFT Face Tracking	Available
osgART	Open source Commercial	Android iOS Windows	Marker NFT	Available
ROS object recognition tabletop package	Open source	Unix Windows	Marker NFT Spacial mapping	Available
SUGAR	Open source	Android Symbian	Marker	Not found
ViSP	Open source Commercial	Android iOS Windows Linux	Marker NFT	Available
VPT7	Free Commercial	Android iOS	Marker NFT Visual search	Available
Vuforia	Free Commercial	Android iOS	Marker NFT	Available

5.6. RQ5: Which are the main challenges to apply Augmented Reality in production environments?

From selected studies, 66% described at least one challenge or limitation of AR utilization in an industrial environment. The limitations were grouped into 5 categories, according to Figure 15, which shows the percentage that each category was cited.

Hardware limitations were one of the most cited difficulties, representing two main barriers,with the first barrier concerning the production layout and user mobility. Studies like Syberfeldt et al. (2016); Danielsson et al. (2018) argue that users need to have both their hands and visual field free majority of the time that they are working, to properly execute their activity. Therefore, using hand-held devices or projectors are not appropriate for these environments. Additionally, Syberfeldt et al. (2017); Chalhoub and Ayer (2018) cited that noise and safety conditions can affect user performance while using vocal commands with AR systems. An alternative to this constraint is the use of a HMD, but their use is the second issue argued by authors because they are not well functioning at a certain level (Blanco-Novoa et al., 2018; Liu et al., 2017).

Related to hardware limitations, user health was also an impediment point to the technology dissemination when HMDs are used. These devices utilize a field of view that is smaller than human's, which could cause headaches, dizziness nausea after a prolonged period of use. Additionally, the HMD is associated with discomfort caused by the weight and a limitation of usage for users that need to use regular gog-

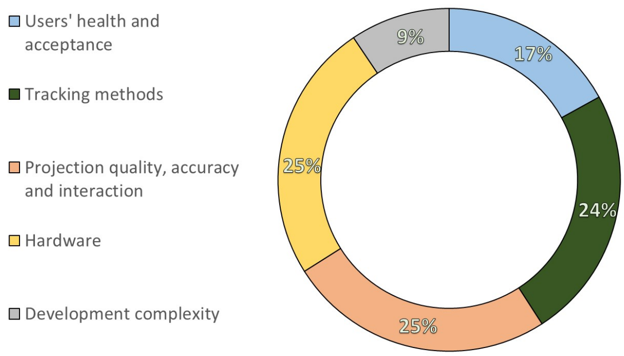

Figure 15: Percentage of main challenges and constraints of industrial AR usage on production environment.

gles (Nee et al., 2012; Fiorentino et al., 2014; Yew et al., 2016; Hao and Helo, 2017). However, just 16% of primary studies declared that ergonomics was relevant in the development. Not only the physical aspect was discussed in primary studies, but also the psychological aspect. Some studies reported that user confidence in the technology could also affect the results and implementation of AR (Rios et al., 2013; Blattgerste et al., 2017).

Tracking method was cited by primary studies as an additional challenge. Markers usage is not ideal for a production environment because they can be obstructed by assembly components, tools shadows during production the processes (Fang et al., 2014). Additionally, the size and position of markers can be a barrier during the execution of activities (Liu and Seipel, 2017). Markerless methods were also investigated; however these methods have not been developed to maturity and require a long setup time, as they have difficulties in mapping the environment (Soete et al., 2015), and virtual objects instabilities (Hou et al., 2014).

The main category discussed was the quality and accuracy of the virtual elements. Around 22% of primary studies declared that the virtual object quality 38% its accuracy, were considered relevant to the application development. The main issues identified were related to the virtual object not having distinct shapes, low resolution out of real position. Two main points cause this problem. First, without an accurate tracking method, the virtual elements cannot be correctly placed; however, no study analyzed general tolerances using different tracking methods, hardware, light conditions or distances from recognition references. Second, bad image quality is associated with latency. According to Lee (2018); Liu et al. (2017) real-time rendering algorithms have to be optimized to provide better visualization.

Finally, some studies reported that developing an AR application requires deep knowledge, what often associates with high implementation costs (Kollatsch et al., 2014; Herr et al., 2018) and lack of information concerning new developments (Syberfeldt et al., 2017).

5.7. Industrial AR future

Future AR developers should consider including tests in a manufacturing environment or simulating these conditions by changing illumination and generating sound effects during operation. Furthermore, developers should evaluate user mobility according to the activity needs, while considering user time required to set up and interact with the system. Gamification techniques are also advisable as a way to make the user, who is not accustomed to the technology, feel more comfortable and confident. Another crucial aspect for applications' developers to consider is that the selected visualization device should be ergonomic during interaction and visualization in an extended use period; moreover, the device should not limit or increase the necessary movement required to execute the main activity.

New hardware also should be considered to improve AR use in industrial environments. The main challenge, in particular for patents creation, is to produce lighter devices that can be attached to the user's body in a way that does not limit user vision or mobility. AR development tools that are more intuitive to create the augmented experience are also necessary to promote the technology. More intuitive tools offer manufacturing developers the opportunity to create and change the AR content without the need for expert, making it flexible to industrial applications.

Finally, future researches should analyze AR impacts on the environment, measuring the technology demand on nature and comparing it to traditional methods. This analysis can attract investors to the technology if results are better than traditional methods, or can lead to proposed changes to devices. Health aspects also must be studied. Understanding users' physical and mental impacts when exposed to a long period of use with the augmented information and the visualization device is essential.

6. Conclusion

This paper complements previous AR surveys by compiling how AR has been developed and applied in general industrial environments. The survey analyzed research papers and patents to expose AR improvements and limitations, while also proposing an approach to tackle developer's challenges and meeting user's needs.

Identified AR applications show some disruptive innovations, such as eliminating the need for on-site experts, with solutions proposing the use of remote assistance or robot programming by identifying user movements. However, most applications are incremental as they are a different and more efficient way to transmit information, without making traditional methods obsolete.

The present study also identified that most AR researches happened in a general context. As the number of publications increases every year, it looks like those companies are interested in finding solutions without exposing their production process and with a low implementation risk, as these solutions were previously tested.

AR applications in industrial environments are directly associated with complex processes. The technology used is a critical factor to improve process flexibility, which is the key to a company's success. Process flexibility is achieved by not only providing information to manufacturing, but also by improving inspection, providing more efficient logistics, support maintenance process monitoring.

Production environments. tend to utilize HMD devices. The primary motivation for their application is the mobility that they afford to users during the manufacturing process. However, it is possible to identify that they still need some technological improvements to improve user's comfort while wearing the device. Ergonomics and legal aspects of their usage is still unknown, so they still represent a significant risk to companies employing the device.

Designing for AR can be an alternative to face the tracking challenge. During the design phase some characteristics in products and processes can be defined to be used as natural markers. The use of these natural markers can improve the user's mobility, as the scene has many references to calculate the virtual object pose. Also design for Augmented Reality can promote the use of hardware that are cheaper than HMD, making AR more accessible and easier to be applied to companies of different sizes.

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HIGHLIGHTS

Title: A Survey of Industrial Augmented Reality

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Highlights:

- State of the art review of Augmented Reality in industrial environments.
- Augmented Reality applications to improve complexes process.
- Wearable devices and markerless tracking are tendencies to improve Augmented Reality applications in production environments.
- Considerations to implement Augmented Reality
- Future developments to improve Augmented Reality use in industrial environments.