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IISE Transactions

ISSN: 2472-5854 (Print) 2472-5862 (Online) Journal homepage: https://www.tandfonline.com/loi/uiie21

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To cite this article: Eleonora Bottani & Giuseppe Vignali (2019) Augmented reality technology in the manufacturing industry: A review of the last decade, IISE Transactions, 51:3, 284-310, DOI: 10.1080/24725854.2018.1493244

To link to this article: https://doi.org/10.1080/24725854.2018.1493244

Accepted author version posted online: 03 Jul 2018.
Published online: 22 Feb 2019.

IISE TRANSACTIONS
2019, VOL. 51, NO. 3, 284–310
https://doi.org/10.1080/24725854.2018.1493244

Augmented reality technology in the manufacturing industry: A review of the last decade

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ABSTRACT

The aim of this article is to analyze and review the scientific literature relating to the application of Augmented Reality (AR) technology in industry. AR technology is becoming increasingly diffuse, due to the ease of application development and the widespread use of hardware devices (mainly smartphones and tablets) able to support its adoption. Today, a growing number of applications based on AR solutions are being developed for industrial purposes. Although these applications are often little more than experimental prototypes, AR technology is proving highly flexible and is showing great potential in numerous areas (e.g., maintenance, training/learning, assembly or product design) and in industrial sectors (e.g., the automotive, aircraft or manufacturing industries). It is expected that AR systems will become even more widespread in the near future.

The purpose of this review is to classify the literature on AR published from 2006 to early 2017, to identify the main areas and sectors where AR is currently deployed, describe the technological solutions adopted, as well as the main benefits achievable with this kind of technology.

ARTICLE HISTORY
Received 6 October 2016
Accepted 18 June 2018

KEYWORDS
Augmented reality (AR); manufacturing industry; literature review

1. Introduction and background on AR systems

Augmented Reality (AR) is a term used to identify a set of technologies that allows the view of real world environment to be "augmented" by computer-generated elements or objects (Van Krevelen and Poelman, 2010). More specifically, AR describes a mediated reality, where the visual perception of the physical real-world environment is enhanced by means of computing devices. Compared with Virtual Reality (VR), i.e., a set of technologies that allow the user to interact with a computer in a simulated environment (either a simulation of the real world or an imaginary world, Khan *et al.* (2011)), AR does not aim to replace the real world with a simulated one and is consequently often classified as a Mixed Reality (MR) system. MR is a mix of reality and VR, encompassing both AR and augmented virtuality, *via* immersive technology (Milgram and Kishino, 1994).

The first AR prototypes, created by computer graphics pioneer Ivan Sutherland and his students at Harvard University and the University of Utah, appeared in the late-1960s and exploited a see-through display fitted to a helmet to present 3D graphics (Tamura, 2002). During the 1970s and 1980s, mobile devices such as the Sony Walkman (1979), digital watches and personal digital organizers were introduced. This paved the way for wearable computing in the 1990s as personal computers became small enough to be worn at all times (Van Krevelen and Poelman 2010). It was only in the early-1990s that the term "augmented reality" was coined by Caudell and Mizell (1992), both scientists at the Boeing Corporation, who developed an experimental AR system to help workers put together wiring harnesses. Since the late-1990s, AR has been a specific field of research, as demonstrated by the fact that several conferences on AR have been held (e.g., the International Workshop and Symposium on AR and the International Symposium on MR). By classifying the literature published in the 1990s, Azuma (1997) found six main classes of potential AR applications, such as medicine, maintenance/repair, annotation, robotics, entertainment, and military settings; in an update of that review, new areas were identified, namely outdoor, mobile AR and collaborative AR (Azuma *et al.*, 2001). Recently, Johnson *et al.* (2011) predicted that AR technologies would have emerged more fully within the next 2 to 3 years; learning, education, and entertainment were identified among the most promising areas of AR application. Georgel (2011) coined the term "Industrial Augmented Reality" (IAR) to describe the use of AR to support an industrial process and identified product design, manufacturing, assembly, maintenance/inspection, and training as the key areas for IAR applications.

The success of any emerging technology is typically the result of various aspects, including social and technical issues (Liao, 2016). From a technical point of view, since the late-1990s it has become much easier to develop AR applications rapidly, thanks to freely available software toolkits

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(e.g., the ARToolKit) and the development of camera systems able to analyze the physical environment in real time and relate positions between objects and environment in that period. This type of camera system now represents the basis for the integration of virtual objects with reality in AR systems. The smart phone adoption and the proliferation of AR browser applications are further aspects that contribute to the diffusion of AR solutions (Johnson *et al.*, 2011). From a social perspective, usually AR is not perceived as a tool to replace human workers, but rather to help them; this may do well also against social issues relating to its industrial deployment (Azuma, 1997). As a result, today AR solutions are increasingly diffuse in industrial contexts, where they are developed for different ends (Nee *et al.*, 2012). Personal information or personal assistance applications have been developed on the basis of AR systems (Höllerer and Feiner, 2004). Other applications are reported in the tourism sector: Vlahakis *et al.* (2001) developed ARCHEOGUIDE, which reconstructs a cultural heritage site in Olympia, Greece. Other areas interested in AR applications include the military (Henderson and Feiner, 2009; van Krevelen and Poelman, 2010), automotive (Regenbrecht *et al.*, 2005), and medical sectors (Vogt *et al.*, 2006). Construction is the industry with the highest number of AR applications (Behzadan *et al.*, 2015). In this context, AR applications are well established and used for many purposes, including building damage reconnaissance, georeferenced visualization of underground utilities, collaborative design and information delivery.

An emerging area of AR applications is the manufacturing industry, which is concerned with the process of transforming raw materials into finished goods with added value. Due to their complex internal processes and the increasing globalization of supply chains, manufacturing companies need real-time information exchanges at the various stages of the product lifecycle, i.e., design, prototyping, production, assembly, maintenance/repair, etc. In this scenario, AR can be of great help, due to its capability to simulate, assist and improve its processes before they are carried out (Ong *et al.*, 2008). Indeed, the virtual objects display information that the user cannot directly detect with his own senses; the information conveyed by the virtual objects may help a user perform most of the product-related tasks (Azuma, 1997). AR applications to the manufacturing industry have been developed for several purposes, including process monitoring and control, real-time evaluation of plant layout, plant and machinery maintenance, plant and building construction, as well as for enhancing industrial safety (Georgel, 2011). Moreover, authors argue that the future of mobile technology promises to revolutionize AR mobile applications in the manufacturing industry (Carmigniani *et al.*, 2011). Despite this, AR applications in manufacturing are perceived to be still in an exploratory stage (Ong *et al.*, 2008) and full-scale deployments of IAR solutions have been carried out only in a limited number of cases (Georgel, 2011).

On the basis of these premises, this study proposes a literature review of recent AR studies in industry, expressly focusing on those which may help to carry out operations typical of the manufacturing industry (e.g., assembly, maintenance or facility management). Besides the fact that AR applications are increasingly used within the manufacturing industry, we decided to target this context as it is one of Italy's most prominent industrial sectors. Italy is currently the fifth largest manufacturing producer in the world (OECD, 2013). In our analysis of the manufacturing industry, we have not focused on the other industrial sectors, and in particular the construction industry, despite the wide use of AR systems in this context, as it has been analyzed in the recent review by Behzadan *et al.* (2015). The overall aim of this study is to categorize the recent literature, examine the state-of-the-art solutions and highlight the key benefits of AR technology within the manufacturing industry.

The remainder of this article is organized as follows. Section 2 details the research methodology adopted for the literature survey and presents some preliminary information about the studies analyzed. Section 3 details the survey results and includes not only descriptive statistics on the sample of papers reviewed, but also their categorization and their detailed analysis. Section 4 summarizes the key findings from the review, discusses the related scientific and practical implications, and indicates potential future research.

2. Methodology

2.1. Survey methodology

The research methodology chosen for this study is systematic literature review (Tranfield *et al.*, 2003). This kind of review requires two steps (Alderson *et al.*, 2004). First, the inclusion criteria have to be clearly specified, with the purpose of correctly selecting the studies to be reviewed. To this end, we have only included in the review studies:

1. in English and published in peer-reviewed international journals;
2. that expressly focus on AR (as opposed to VR) solutions in the manufacturing industry.

Because of a previous review study (Ong *et al.*, 2008) that included papers published up to 2005, the publication timespan was limited to be between 2006 and 2017.

The first step of a systematic literature review is to define the strategy of locating and selecting the studies. In this article, a computerized search was made using three different databases: Scopus (http://www.scopus.com/), Web of Science (WOS) (https://apps.webofknowledge.com), and Ebsco (https://www.ebscohost.com/) to identify pertinent studies. The search was performed following the steps shown in Figure 1.

As can be seen from Figure 1, we began by making a search query on Scopus, WOS, and Ebsco databases with the general keywords or topics "augmented reality" + "machine" or "equipment," "manufacturing," "maintenance," "safety," "risk," "emergency," "hazard," "assembly". The search, which was carried out in its final version between December 2016

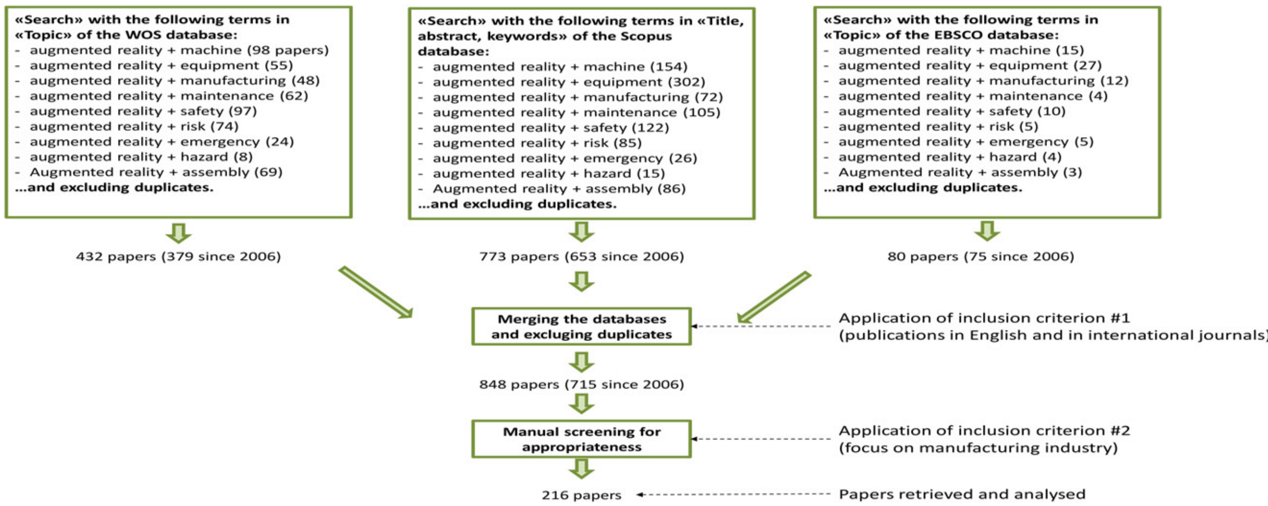


Figure 1. Scheme of the query and related results.

and February 2017, returned a total of 1285 papers, which were reduced to 848 after merging the results from the databases and excluding duplicates. In this phase, we also excluded articles that turned out to be preliminary conference papers, whose extended version was published later on an international journal, or articles that were erroneously classified as journal papers in the scientific databases, but were actually conference papers. Out of the 848 papers, 715 were published since 2006. By applying the second inclusion criterion, we excluded the studies that did not target the manufacturing industry, but rather were carried out in a different context, e.g., in the medical field or in the construction sector. We obtained 216 papers in English published in peer-reviewed international journals since 2006 and targeting the manufacturing industry.

These papers were all retrieved and examined individually, by checking the title, abstract and main contents. Forty-two of these papers were further excluded from the analysis, because of their limited relevance to AR or because they focused on VR instead of AR, obtaining 174 papers, which constitute the sample of studies reviewed. The whole set of 216 papers retrieved and examined is reported in Table 1.

2.2. Classification and analysis

The 174 papers reviewed were initially classified into four groups (see Table 1):

1. Review papers (15).
2. Technical papers (69), i.e., papers whose main focus is on the development, calibration or refinement (and possibly testing) of a technical hardware or software feature of the AR system.
3. Application papers (70), i.e., papers whose main focus is on the development, deployment and possibly testing of the AR solution in a real or laboratory environment.
4. Conceptual papers (20), i.e., papers that do not either develop a new AR solution or apply an existing AR system, but rather discuss some specific aspects or issues of AR adoption in industry.

For the whole sample of papers reviewed, we provide some descriptive statistics on the year of publication and geographical origin of the study, to verify whether the focus on IAR systems has increased over time and is equally distributed across the various countries where it has been analyzed (subsection 3.1). Then, the different groups of papers are analyzed (subsection 3.2). Review papers and conceptual papers, which are fewer in number, are examined almost individually, by providing an overview of the main topics treated. As application papers and technical papers are more numerous, the framework for their analysis is grounded on the classification of the study keywords as way to capture the essential topics covered, according to Fadlalla and Amani (2015). These authors suggested evaluating two main parameters, namely the frequency of use of the keywords and their persistence. "Frequency" refers to the number of times a concept is used as a keyword by researchers; from a quantitative perspective, it is measured as the number of articles where a given keyword appears. "Persistence" is a time-based measure reflecting the continuity of a given concept over time; it can be measured as the number of years since a concept was first introduced as a keyword. Such analysis is expected to generate an overview of the main research areas relating to AR in industry, as well as to categorize the research topics on the basis of their importance to the scientific community. We used the "Export" function of Scopus/WOS to retrieve the keywords of technical and application papers automatically; for the papers found on the Ebsco database, keywords were retrieved manually.

As further aspects of the analysis, the main fields of application of AR, the technological solutions deployed, and the results achieved from the AR usage are described in Sections 3.3, 3.4, and 3.5, respectively, for the different group of papers and together with their evolution in time (where appropriate).

Table 1. Full list of papers retrieved and analyzed.

		Classification			
Reference	*Included (Y/N)*	*Application paper*	*Technical paper*	*Review paper*	*Conceptual paper*
Adcock & Gunn (2015)	Y	X			
Ahn & Han (2012)	Y		X		
Ajanki *et al.* (2011)	Y		X		
Al-Mouhamed *et al.* (2006)	Y		X		
Anastassova & Burkhardt (2009)	Y				X
Armesto *et al.* (2008)	N				
Aromaa & Väänänen (2016)	Y				X
Arshad *et al.* (2016)	Y		X		
Aschenbrenner *et al.* (2016)	Y	X			
Aurich *et al.* (2009)	N				
Behzadan & Kamat (2010)	Y		X		
Benbelkacem *et al.* (2013)	Y		X		
Bhowmik (2017)	N				
Biocca *et al.* (2007)	Y		X		
Bleser *et al.* (2015)	N				
Blum *et al.* (2013)	N				
Borsci, Lawson, Jha, Burges and Salanitri (2016)	N				
Borsci, Lawson, Salanitri and Jha (2016)	N				
Bottecchia *et al.* (2009)	Y	X			
Bugarić *et al.* (2014)	N				
Buker *et al.* (2012)	N				
Candela *et al.* (2014)	Y		X		
Canessa *et al.* (2014)	Y		X		
Carmigniani *et al.* (2011)	Y			X	
Caruso *et al.* (2015)	Y		X		
Cauchard *et al.* (2012)	N				
Celozzi *et al.* (2013)	N				
Chandaria *et al.* (2007)	Y		X		
Chen (2014)	Y				X
Chen, Hong and Wang . (2014)	Y		X		
Chen, Jin and Wang (2014)	N				
Chen, He, Mo, Li and Yang, (2016)	Y	X			
Chen, Chi, Kang and Hsieh . (2016)	Y	X			
Cheok *et al.* (2007)	N				
Chimienti *et al.* (2010)	Y				X
Choi *et al.* (2015)	N				
Csapó & Wersényi (2013)	N				
De Crescenzio *et al.* (2011)	Y	X			
De Lucia *et al.* (2011)	Y			X	
De Marchi *et al.* (2013)	Y		X		
De Marsico *et al.* (2014)	N				
Di Cecca *et al.* (2016)	Y	X			
Doshi *et al.* (2017)	Y	X			
Duarte *et al.* (2010)	N				
Eck *et al.* (2015)	Y		X		
El Kabtane *et al.* (2016)	Y	X			
Elia *et al.* (2016)	Y				X
Espíndola *et al.* (2013)	Y	X			
Ferrise *et al.* (2013)	Y	X			
Fiorentino *et al.* (2013)	Y	X			
Fiorentino *et al.* (2014)	Y				X
Fiorentino *et al.* (2016)	Y	X			
Fox (2010)	Y				X
Fox *et al.* (2011)	N				
Franceschini *et al.* (2016)	Y	X			
Galambos *et al.* (2015)	N				
Gattullo *et al.* (2015)	Y		X		
Gavish *et al.* (2015)	Y	X			
Gedik & Alatan (2013)	Y		X		
Geng *et al.* (2015)	N				
Georgel *et al.* (2009)	Y		X		
Gimeno *et al.* (2013)	Y		X		
Golański et al. (2014)	Y	X			
Gonzalez-Sanchez *et al.* (2012)	Y	X			
Green *et al.* (2008)	Y			X	
Gurevich *et al.* (2015)	Y	X			
Hagbi *et al.* (2011)	Y		X		
Haist (2008)	Y				X
Han & Zhao (2015)	Y		X		
Han *et al.* (2011)	N				
Harwood & Revell (2017)	N				
Heemskerk *et al.* (2011)	N				

(*continued*)

Table 1. Continued.

Reference	Included (Y/N)	Classification			
		Application paper	*Technical paper*	*Review paper*	*Conceptual paper*
Heikkinen & Handroos (2013)	N				
Henderson & Feiner (2010)	Y		X		
Henderson & Feiner (2011)	Y	X			
Hou & Wang (2013)	Y				X
Hovanec *et al.* (2014)	Y			X	
Hovanec *et al.* (2015)	N				
Huang *et al.* (2012)	Y	X			
Huang *et al.* (2016)	Y		X		
Huenerfauth (2014)	Y				X
Igarashi & Inami (2015)	Y			X	
Irizarry *et al.* (2014)	Y	X			
Itoh *et al.* (2015)	Y		X		
Januszka & Moczulski (2011)	Y	X			
Jiang & Nee (2013)	Y	X			
Jiang *et al.* (2014)	Y	X			
Jimeno-Morenilla *et al.* (2013)	Y		X		
Jung *et al.* (2010)	Y		X		
Kadavasal & Oliver (2009)	N				
Karbasi *et al.* (2016)	N				
Kellner *et al.* (2012)	Y		X		
Kim & Lee (2016)	Y		X		
Kim & Moon (2013)	Y	X			
Klein & Murray (2010)	Y		X		
Koch *et al.* (2014)	Y		X		
Krajcovic *et al.* (2014)	Y	X			
Lakshantha & Egerton (2016)	Y	X			
Lamberti *et al.* (2015)	Y			X	
Lamberti *et al.* (2017)	Y		X		
Lambrecht *et al.* (2013)	Y		X		
Langley *et al.* (2016)	Y				X
Langlotz *et al.* (2011)	Y		X		
Lee & Akin (2011)	Y	X			
Lee & Rhee (2008)	Y		X		
Lee *et al.* (2009)	Y	X			
Lee, Lee, Kim and Kim (2010)	Y	X			
Lee *et al.* (2010)	Y	X			
Lee, Billinghurst and Woo (2011)	Y		X		
Lee, Han and Yang (2011)	N				
Lee *et al.* (2016)	Y		X		
Leu *et al.* (2013)	Y			X	
Li *et al.* (2014)	N				
Lijun *et al.* (2008)	Y		X		
Liu & Zhang (2015)	Y		X		
Liu *et al.* (2013)	Y		X		
Liu *et al.* (2014)	Y		X		
Liu *et al.* (2015)	Y	X			
Liu *et al.* (2016)	Y		X		
Liverani *et al.* (2006)	N				
Luh *et al.* (2013)	Y	X			
Makris *et al.* (2013)	Y		X		
Martínez *et al.* (2013)	Y	X			
Monroy Reyes *et al.* (2016)	Y	X			
Morkos *et al.* (2012)	Y	X			
Moser *et al.* (2015)	Y		X		
Mossel (2015)	Y		X		
Mourtzis *et al.* (2013)	Y		X		
Mourtzis *et al.* (2015)	N				
Mourtzis *et al.* (2017)	Y	X			
Nakai & Suzuki (2016)	Y	X			
Nakanishi & Sato (2015)	Y				X
Nakanishi *et al.* (2010)	Y				X
Narducci *et al.* (2016)	N				
Nathanael *et al.* (2016)	N				
Nazir *et al.* (2013)	N				
Nedel *et al.* (2016)	N				
Nee *et al.* (2012)	Y			X	
Neges *et al.* (2017)	Y	X			
Neubert *et al.* (2012)	Y		X		
Ng *et al.* (2013)	Y	X			
Novak-Marcincin & Novakova-Marcincinova (2013)	Y				X
Novak-Marcincin *et al.* (2013)	Y	X			
Oliveira *et al.* (2013)	Y			X	

(*continued*)

Table 1. Continued.

Reference	Included (Y/N)	Classification			
		Application paper	*Technical paper*	*Review paper*	*Conceptual paper*
Olsson *et al.* (2012)	Y				X
Ong & Wang (2011)	Y	X			
Ong & Zhu (2013)	Y	X			
Ong *et al.* (2007)	Y		X		
Ong *et al.* (2008)	Y			X	
Orlosky *et al.* (2015)	Y		X		
Pai *et al.* (2015)	Y		X		
Pai *et al.* (2016)	Y		X		
Pang *et al.* (2006)	Y	X			
Park & Kim (2013)	Y	X			
Park *et al.* (2009)	Y	X			
Piekarski (2006)	Y	X			
Pirvu *et al.* (2016)	Y		X		
Radkowski (2016)	Y		X		
Radkowski *et al.* (2015)	Y				X
Rajendran *et al.* (2015)	Y			X	
Rapaccini *et al.* (2014)	Y				X
Re *et al.* (2016)	Y				X
Rehman & Cao (2017)	Y				X
Reif & Günthner (2009)	Y	X			
Reif *et al.* (2010)	Y	X			
Reinhart & Eursch (2008)	Y	X			
Rohidatun *et al.* (2016)	Y		X		
Sangineto & Cupelli (2012)	N				
Sanín *et al.* (2007)	Y		X		
Schega *et al.* (2014)	Y		X		
Shaaban *et al.* (2015)	Y	X			
Siewiorek & Smailagic (2016)	N				
Stork & Schubö (2010)	Y			X	
Suhaifi *et al.* (2015)	Y		X		
Tatić& Tešić (2017)	Y	X			
Tegeltija *et al.* (2016)	Y	X			
Tsai *et al.* (2012)	Y	X			
Tuma *et al.* (2016)	Y		X		
Turner *et al.* (2016)	N				
Ueng & Chen (2016)	Y		X		
Umetani *et al.* (2014)	Y	X			
Valentini (2009)	Y	X			
Van West *et al.* (2007)	Y		X		
Vanderroost *et al.*(2017)	Y			X	
Verbelen *et al.* (2014)	Y		X		
Vignais *et al.* (2013)	Y	X			
Vitzthum & Hussmann (2006)	Y		X		
Vogl *et al.* (2006)	Y		X		
Vukobratovic (2010)	N				
Wang & Dunston (2006)	Y		X		
Wang *et al.* (2011)	N				
Wang, Ong and Nee (2013)	Y		X		
Wang, Ng, Ong and Nee (2013)	Y		X		
Wang *et al.* (2016a)	Y			X	
Wang *et al.* (2016b)	Y	X			
Wang *et al.* (2016c)	Y	X			
Webel *et al.* (2013)	Y	X			
Weidlich *et al.* (2008)	Y				X
Weinert *et al.* (2008)	Y	X			
Weng *et al.* (2012)	Y		X		
Westerfield *et al.* (2015)	Y	X			
Wójcicki (2014)	Y	X			
Xiong *et al.* (2006)	Y		X		
Xu *et al.* (2017)	Y		X		
Yamauchi & Iwamoto (2010)	Y		X		
Yang *et al.* (2014)	Y	X			
Yannakakis *et al.* (2009)	N				
Yew *et al.* (2016)	Y		X		
Yin *et al.* (2015)	Y			X	
Yuan *et al.* (2008)	Y	X			
Zhang *et al.* (2010a)	Y	X			
Zhang *et al.* (2010b)	Y	X			
Zhang *et al.* (2011)	Y	X			
Zhang *et al.* (2014)	N				
Zhu *et al.* (2013)	Y	X			
Zhu *et al.* (2014)	Y	X			

3. Review results

3.1. Descriptive statistics

We begin by categorizing the groups of papers on the basis of year of publication with the aim of demonstrating increasing interest in AR systems; results are reported in Figure 2.

As can be seen from Figure 2, the number of papers published from 2006 to 2012 was between 5 and 14 papers per year, whereas after that period research on AR has increased, with more than 20 papers per year published from 2013 to 2016. This shows that the interest on AR systems has grown steadily in the last decade and in recent years in particular, with a peak of 30 and 29 papers published in 2016 and 2013, respectively. Another interesting aspect is that technical papers were published with good continuity since 2006; with conceptual papers and review papers appearing in 2008 and since then being published with quite good continuity as well. Obviously, review studies on a given subject can be carried out only after a wide number of research papers have been published. At the same time, conceptual papers discussing specific aspects/issues relating to AR usage or implementation (e.g., psychological issues or technology acceptance issues – see Section 3.2.2) are probably motivated by the development of new technical solutions or by new applications of AR in industry. A key factor that is likely to contribute to the increase in AR research in recent years is the widespread diffusion of mobile devices (smartphones or tablet PCs), which has meant a significant reduction in both the cost and effort required to realize an AR system. In fact, 69% (110 out of 174 papers) of the studies reviewed were carried out in the last 5 years.

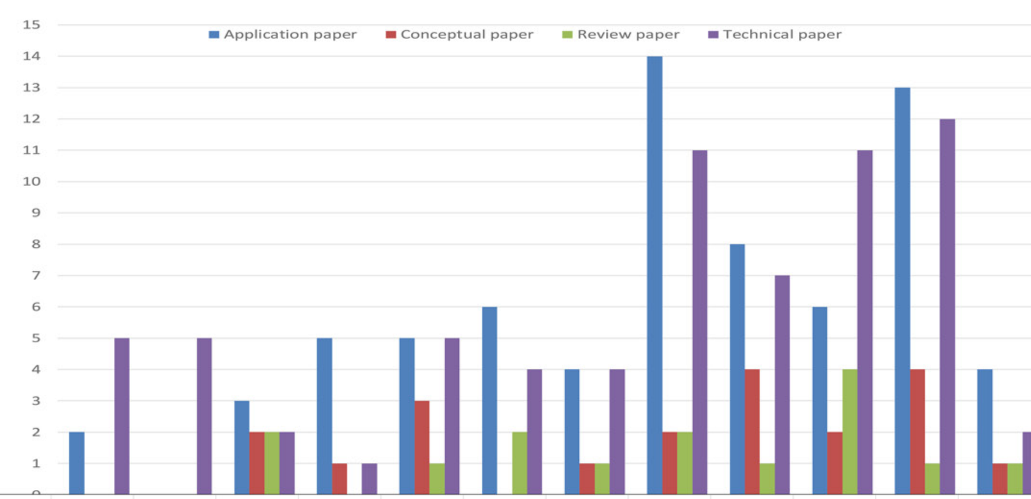
Interesting considerations emerge from the geographical distribution of the studies reviewed, which is shown in Figure 3. To determine the country of the study, if conflicts existed, the nationality of the first author was taken as reference, which is a common approach in review studies (e.g., Gao *et al.* 2017).

Figure 3 shows that the majority of the studies come from Singapore (12.64%), Germany (10.92%), Italy (10.34%), USA (9.77%), and China (7.47%). This result can have a twofold justification. First, many of the companies who are manufacturing industrial devices for AR are located in these countries (Market Reports Center, 2017). Moreover, several well-known research groups dedicated to exploring the use of AR for industrial applications are based in both Germany and the USA (Friedrich, 2002; Raczynski and Gussmann, 2004; Westerfield *et al.*, 2015). In this respect, it is interesting to note that most of the studies carried out in Germany, the USA and China are technical papers, which suggests that these countries are particularly active in exploring new hardware/software AR features and confirms the relationships with the presence of research groups operating in two of these countries. Finally, many countries have carried out very few (i.e., one or two) studies on AR, demonstrating that this technology is still in its early stage of adoption.

3.2. Topics and keywords analysis

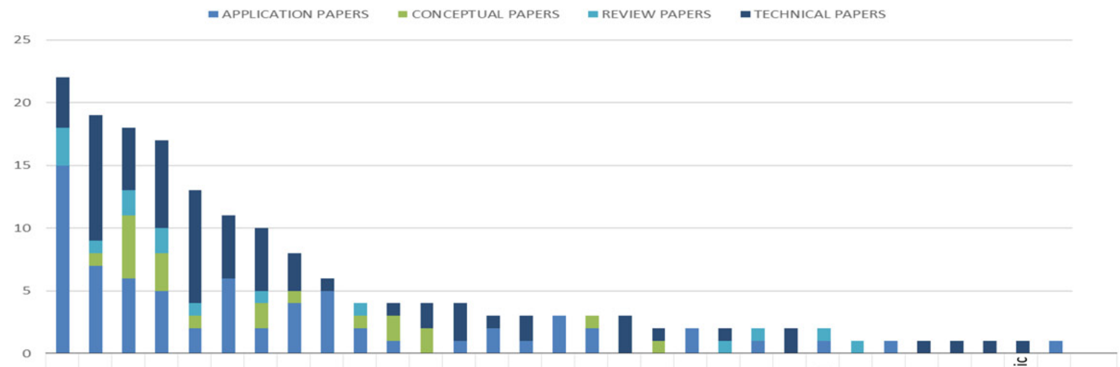
3.2.1. Review papers

The 15 review papers provide a summary of the existing literature about different aspects of AR solutions and applications. These papers propose general state-of-the-art analyses of AR technologies (Carmigniani *et al.*, 2011), with a focus in the main patents (De Lucia *et al.*, 2011), as well as in the manufacturing context (Ong *et al.*, 2008). Other studies review AR systems that can be used for specific purposes, such as to enhance human computer interaction (HCI) (Igarashi and Inami, 2015; Rajendran *et al.*, 2015) or human-robot collaboration (Green *et al.*, 2008). Several papers analyze AR applications devoted to a particular



CLASSIFICATION	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	*Total*
Application paper	2		3	5	5	6	4	14	8	6	13	4	*70*
Conceptual paper			2	1	3		1	2	4	2	4	1	*20*
Review paper			2		1	2	1	2	1	4	1	1	*15*
Technical paper	5	5	2	1	5	4	4	11	7	11	12	2	*69*
Total	*7*	*5*	*9*	*7*	*14*	*12*	*10*	*29*	*20*	*23*	*30*	*8*	*174*

Figure 2. Distribution of the group of papers as a function of the publication year (*Note: partial results for 2017*).



CLASSIFICATION	Singapore	Germany	Italy	USA	China	Korea	Japan	Australia	Taiwan	Slovakia	Finland	UK	Malaysia	Israel	Greece	Poland	France	Spain	Canada	Serbia	Belgium	Brazil	Austria	New Zealand	India	Morocco	Turkey	Saudi Arabia	Algeria	Czech Republic	Mexico	*Total*
Review paper	3	1	2	2	1		1			1											1	1		1	1							*15*
Conceptual paper		1	5	3	1		2	1		1	2	2					1		1													*20*
Technical paper	4	10	5	7	9	5	5	3	1		1	2	3	1	2			3	1		1		2				1	1	1	1		*69*
Application paper	15	7	6	5	2	6	2	4	5	2	1		1	2	1	3	2			2		1		1		1					1	*70*
Total	*22*	*19*	*18*	*17*	*13*	*11*	*10*	*8*	*6*	*4*	*4*	*4*	*4*	*3*	*3*	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*174*

Figure 3. Geographic distribution of the studies reviewed.

industrial task; the most investigated tasks are assembly (Stork and Schubö, 2010; Leu *et al.* 2013; Wang *et al.*, 2016a) , maintenance (Oliveira *et al.*, 2013; Lamberti *et al.* 2015), design (Nee *et al.*, 2012; Yin *et al.*, 2015), safety/ergonomics (Hovanec *et al.*, 2014) and food logistics (Vanderroost *et al.*, 2017).

3.2.2. Conceptual papers

Conceptual papers mainly include empirical/statistical studies and position papers, with the only exception of the study by Elia *et al.* (2016), who proposed a decision support system to help production managers in selecting the most efficient AR solution to be applied in specific manufacturing processes.

Position papers typically describe the potentials of AR usage in different fields, encompassing finite elements analysis studies (Weidlich *et al.*, 2008), virtual manufacturing (Novak-Marcincin and Novakova-Marcincinova, 2013), mobile learning (Chen, 2014) and lean manufacturing, this latter in terms of waste reduction and improvement in process efficiency (Huenerfauth, 2014). Anastassova and Burkhardt (2009) discussed the benefits of AR as a tool to solve some typical training problems for automotive service technicians. The study by Langley *et al.* (2016) also focused on the effectiveness of AR systems for training of users. Other position papers provided guidelines for AR implementation, either in general terms (Chimienti *et al.*, 2010) or for the deployment of AR in the specific areas, e.g., assembly and remote maintenance (Haist, 2008). Fox (2010), instead, described the requirements to properly design ICT tools for the implementation of AR.

Looking at the statistical studies, Radkowski *et al.* (2015) evaluated different visual features for the development of AR-based assembly instructions with an increasing level of difficulty. Their hypothesis with this study was that the complexity of the visual feature should comply with the difficulty of the assembly task; therefore, the ultimate aim was to associate different types of visual features of AR systems to different levels of assembly task complexity. Again in the field of assembly, Hou and Wang (2013) evaluated the impact of "gender" on the post-training performance of novice assemblers, by analyzing the learning curves of test users with two assembly treatments (i.e., AR versus 3D manuals). Similar analyses were carried out by Fiorentino *et al.* (2014) and Re *et al.* (2016), who evaluated empirically the effectiveness of maintenance operations assisted with interactive AR instructions compared with paper instructions, in terms of execution time and error rate of the test users. A technical comparison of two solutions for AR, i.e., a wearable head-mounted device and a hand-held device (e.g., smartphone), versus paper solutions was also carried out by Rehman and Cao (2017). Aromaa and Väänänen (2016) compared an AR prototype and a VR one in terms of their suitability to support human factors/ergonomics evaluation during the design phase.

Some statistical studies have focused on the acceptance of AR technology. Nakanishi and Sato (2015) evaluated the psychological and physiological effect of digital manuals presented by a retinal imaging display on workers in the manufacturing industry. Rapaccini *et al.* (2014) provided the results of a field study of user acceptance of AR to support the delivery of field services (e.g., maintenance activities) on installed products, and Olsson *et al.* (2012) carried out a similar study to evaluate the user acceptance, potentials and risks associated to five different mobile AR scenarios. Nakanishi *et al.* (2010) evaluated the situations where the use of Head-Mounted Displays (HMDs) is really effective and can be applied instead of (or in addition to) the traditional auditory/visual instructions.

3.2.3. Technical papers

The analysis of the authors' keywords for the technical papers generated an original list of 304 different terms. For six papers, neither the author's keywords or index keywords were available – these studies have obviously been excluded from this analysis. It should be mentioned that the general keyword "augmented reality" (or "AR") was also excluded from the analysis, because it was originally used to make the

Table 2. Frequency of keywords of the technical papers and year of appearance.

Keyword	*Frequency*	*Persistence*	*Percentage (%)*	*Year of first appearance*
3D	12	11	4.62	2006
Tracking	9	9	3.46	2008
Interaction	8	7	3.08	2010
Assembly	7	10	2.69	2007
VR	6	10	2.31	2007
Calibration	5	5	1.92	2012
User interface	5	11	1.92	2006
Ergonomics	4	4	1.54	2013
Computer aided design (CAD)	4	11	1.54	2006
Mobile	4	6	1.54	2011
HMD	3	7	1.15	2010
Optical see-through (OST)	3	5	1.15	2012
Maintenance	3	10	1.15	2007
Camera	3	10	1.15	2007
Training	3	2	1.15	2015
Control	3	9	1.15	2008
Human-machine interaction (HMI)	3	10	1.15	2007
Display	3	11	1.15	2006
Manufacturing	3	4	1.15	2013
Eye-tracking	3	3	1.15	2014
Robotics	3	4	1.15	2013
Gesture	3	4	1.15	2013
Haptic	3	10	1.15	2007
User test	3	3	1.15	2014
Semantics	2	9	0.77	2008
Optical see-through HMD (OST-HMD)	2	2	0.77	2015
Telerobotics	2	11	0.77	2006
Indoor	2	5	0.77	2012
Human-computer interaction (HCI)	2	3	0.77	2014
Information systems	2	10	0.77	2007
Smart factory	2	1	0.77	2016
Ubiquitous computing	2	9	0.77	2008
Footwear	2	4	0.77	2013
Kinetics	2	4	0.77	2013
Pattern recognition	2	6	0.77	2011
Artificial, augmented and virtual reality (AAVR)	2	7	0.77	2010
Scene analysis	2	11	0.77	2006
Handheld AR	2	5	0.77	2012
Sensors	2	9	0.77	2008
Marker	2	7	0.77	2010
Scene structure and integration modeling language (SSIML)	2	11	0.77	2006
Mobile augmented reality (MAR)	2	2	0.77	2015
Finger detection	2	3	0.77	2014
Ontology	2	10	0.77	2007
Algorithm	2	3	0.77	2014
Kinematics	2	2	0.77	2015
Visualization	2	7	0.77	2010
Non-grouped keywords	*108*		*41.54*	

search query on the scientific databases and to identify the studies to review. It would thus turn out to be the most frequent keyword, which could bias the results of the analysis itself.

A preliminary analysis revealed that authors often use slightly different keywords to express a similar (or the same) concept, which was expected. This is the case for "3D" and "three-dimensional," or "assembly design" and "assembly." We consequently screened manually the keywords to identify similarities and group them into the same thematic field. The keywords resulting from the screening and grouping are shown in Table 2. To be more effective, the table focuses on keywords with a frequency of ≥ 2 and therefore it excludes some keywords that are difficult to group with others, as they relate to very specific topics; these are referred to as "non-grouped" keywords and clearly score a frequency of one each.

Table 2 shows that the most relevant research issues of technical papers focus on 3D applications (4.62% of the grouped keywords), tracking (3.46%), interaction problems (3.08%), VR (2.60%), calibration (1.92%), and user interface (1.92%); as far as the application areas are concerned, the technical solutions developed targeted primarily assembly (2.69%), maintenance (1.15%), ergonomics (1.54%), and manufacturing (1.12%).

The persistence of the grouped keywords was therefore assessed to distinguish between research topics that are well-established, emerging or have been debated in the past, but have now disappeared from the scientific literature. By correlating the frequency of the grouped keywords with their persistence, using the data in Table 2, we obtained the results in Figure 4. The graph in Figure 4 was divided into quarters using a horizontal and a vertical line as separators. For the persistence, the horizontal line is set at persistence $=5.5$, corresponding to half of the time-span covered by the studies reviewed. For the frequency, the vertical line is set at frequency $=3.23$, which is the mean of the frequencies for the grouped keywords.

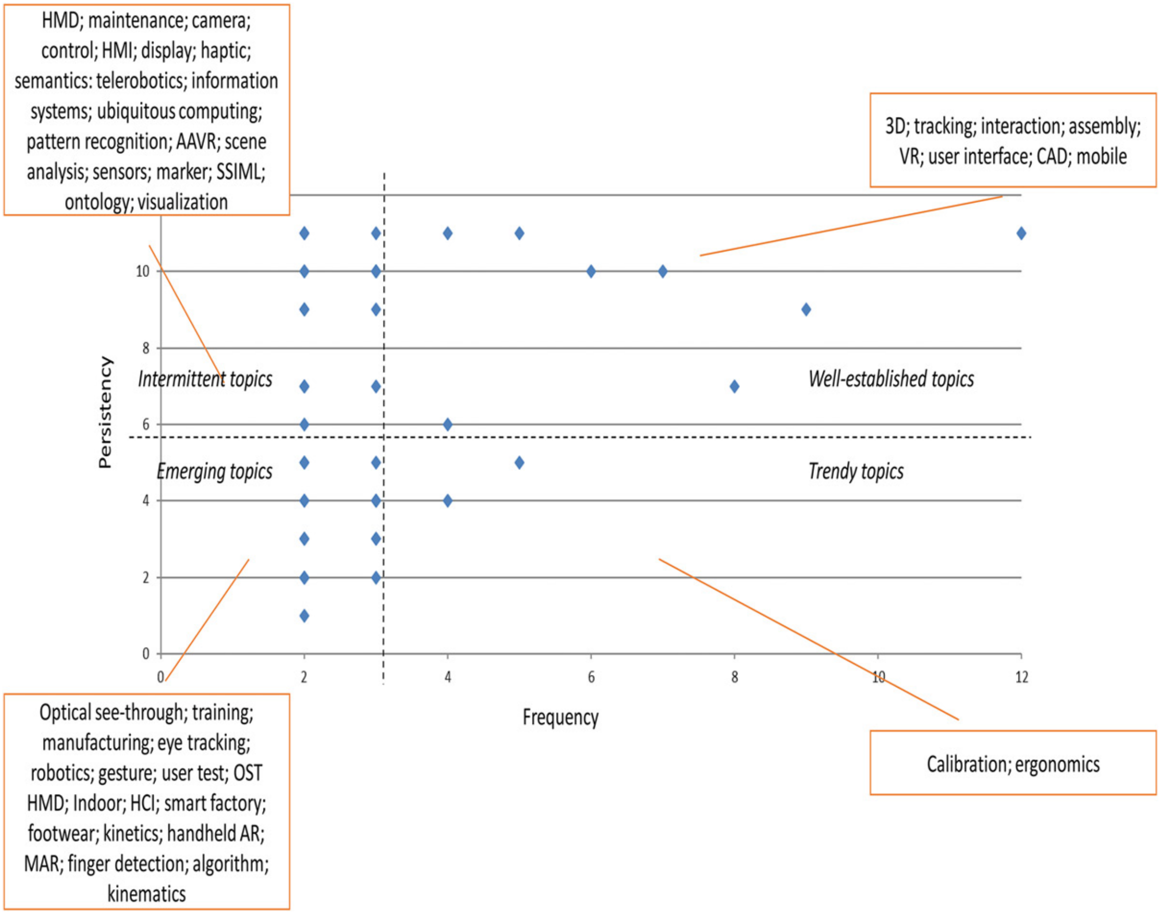


Figure 4. Persistence versus frequency of the keywords for technical papers.

Going back to the aim of analyzing the persistence and frequency concepts, the top-right quarter of Figure 4 includes the grouped keywords which first appeared more than 5.5 years ago and have been used more than 3.23 times overall. This quarter is therefore expected to include "well-established" research topics. The top-left quarter includes the keywords which first appeared more than 5.5 years ago, but have not been used frequently since then. These keywords identify the "intermittent concepts," i.e., concepts that are discussed in the literature in an on-off manner (Fadlalla and Amani, 2015). These are research topics that either the researchers have not agreed on yet, or are relatively frequently tackling changing topics. The bottom-left quarter lists the keywords which have appeared more recently (i.e., less than 5.5 year ago) and have occurred only a few times since then; consequently, these keywords are likely to describe "emerging" research topics. These topics could either disappear early or alternatively become "trendy" topics, which reflect the keywords in the bottom-right quarter; in this case, the research topics seem to be very promising, as the related keywords have appeared recently and have already been used a considerable number of times.

It can be seen from Figure 4 that for technical papers there are eight *well-established* research topics, which refer to 3D, tracking, interaction, VR, AR implementation for assembly/CAD, the development of mobile solutions, or user interfaces. From this list it can be seen that some keywords (e.g., "tracking" or "interaction") falling under the category of well-established research topics actually describe very general concepts or common technical problem when developing AR solutions; therefore, they are likely to be mentioned with a higher frequency by researchers. The use of AR for assembly is primarily motivated by the fact that, on the one hand, assembly processes constitute a significant portion of the cost of a product (Wang, Ong and Nee, 2013; Wang, Ng, Ong and Nee, 2013) and that, on the other one, this cost can be dramatically reduced if a product is assembled according to a well-planned assembly sequence. AR is therefore used to this end, in the attempt to automate the process and enhance its efficiency. Technical papers address, among others, topics relating to the generation of the assembly sequence (Ong *et al.* 2007; Makris *et al.*, 2013), including object recognition issues caused by the particular shape of products (Wang, Ong and Nee, 2013; Radkowski, 2016), or the automated positioning of 3D objects in the assembly guiding system (Chen, Hong and Wang, 2014). Product design/CAD is another well-established field of adoption of AR; in this context, AR is typically used for product customization (Jimeno-Morenilla *et al.*, 2013; Mourtzis *et al.*, 2015), to modify/correct the model (Georgel *et al.*, 2009) or to interact with its (virtual) 3D components (Caruso *et al.* 2015). The proper development of the user interface for AR solutions, including speech recognition features, has been addressed by Ajanki *et al.* (2011), Benbelkacem *et al.* (2013), and Caruso *et al.* (2015). Finally, the development of MAR solutions has been discussed by Biocca *et al.* (2007), Mourtzis *et al.* (2013), Verbelen *et al.* (2014), Han and Zhao (2015), and Kim and Lee (2016).

Intermittent research topics of technical papers include 19 themes, covering AR applications to maintenance and telerobotics, as well as technical issues such as the development of visualization systems or sensors. Among the devices used, HMDs, cameras, and haptic devices fall into this category. Maintenance is a crucial process for facilities and machines to prevent failures and is frequently carried out manually, involving significant time and cost (Koch *et al.* 2014). Maintenance represents an interesting problem domain for the application of AR: indeed, most repair activities are conducted by trained personnel applying established procedures that can be effectively organized into sequences of tasks targeting a particular item, machine, or location (Henderson and Feiner, 2009; Vignali *et al.*, 2018).

In line with these argumentations, in this area technical AR solutions mainly aim at supporting inspectors during the on-field inspection/diagnosis of a machine or when carrying out maintenance tasks (De Marchi *et al.*, 2013), covering also facility maintenance (Koch *et al.*, 2014). The use of AR is expected to avoid delays and possible mistakes during maintenance activities, thus decreasing the related costs (Benbelkacem *et al.*, 2013). Telerobotics is the area of robotics concerned with the control of semi-autonomous robots from a distance (Sheridan, 1989; Goldberg and Siegwart, 2001). In this field, only two technical solutions for the usage of AR were developed, i.e., an AR user interface for nanoscale interaction (Vogl *et al.,* 2006) and a real-time client-server system that can be integrated with 3D AR services (Al-Mouhamed *et al.*, 2006). Visualization issues have been dealt with by Klein and Murray (2010), who proposed a method to model the artifacts produced by a small low-cost camera and add these effects to an ideal pinhole image produced by conventional rendering methods. Sensors (i.e., typically "inertial sensors" of mobile devices) are used in AR environment to estimate the position, inclination, or movement of an object; they have been used to this end by Chandaria *et al.* (2007) and Han and Zhao (2015). An HMD is a display device, worn on the head or as part of a helmet, with one or two small displays; an exhaustive examination of display systems (including HMDs) suitable for adoption in AR environments has been made by Weng *et al.* (2012). Kellner *et al.* (2012) have instead addressed the issue of calibrating these devices for their optimal usage in AR or VR environments. "Haptic" is a term derived from the Greek word "hapticos," i.e., pertaining to the sense of touch; accordingly, haptic technology is a way to recreate the sense of touch by applying forces, vibrations, or motions to the user (El Saddik *et al.*, 2011). Haptic AR systems (also called visuo-haptic augmented reality) enable users to see and touch digital information that is embedded in the real world (Eck *et al.*, 2015). Van West *et al.* (2007) have developed the "haptic tweezer," i.e. a combination of haptic technology and an electrostatic levitation system that allows manipulating objects without direct contact; this technological solution can be useful when manipulating fragile or contaminated components, as it avoids touching them. Another technical solution was developed by Henderson and Feiner (2010), to integrate haptic technology and opportunistic controls, i.e., a class of user interaction techniques for AR applications that support gesturing on and receiving feedback from affordances already present in the domain environment (Henderson and Feiner, 2008).

Emerging research topics (18) include the analysis of technologies for body tracking (e.g., eye-tracking, finger, or gesture detection), optical technologies (primarily OST-HMD), or hand-held technologies. Manufacturing and training are among the emerging application areas of technical papers. An OST-HMD is a wearable device that has the capability of reflecting projected images, as well as allowing the user to see through it using AR. Eye-tracking and OST-HMD have been examined jointly by Moser *et al.* (2015), who carried out a user study to evaluate the registration accuracy produced by three OST-HMD calibration methods, from both an objective (quantitative) and subjective (qualitative) perspective. Similarly, Orlosky *et al.* (2015) have proposed ModulAR, a hardware and software framework designed to improve flexibility and hands-free control of video see-through AR displays; the framework integrates eye-tracking for on-demand control of vision augmentations, such as optical zoom or field of view expansion. Looking at gesture tracking, Kim and Lee (2016) have proposed a method for naturally and directly manipulating 3D AR objects through touch and hand gesture-based interactions in hand-held devices; the touch gesture is used for the AR object selection, whereas the natural hand gesture enables the direct and interactive manipulation of the selected objects. Lambrecht *et al.* (2013) have applied a similar approach, i.e., a combination of marker-less gesture recognition and MAR, to the programing of industrial robots. Caruso *et al.* (2015) have instead proposed an interactive AR system that enables the user to freely interact with virtual objects integrated in a real environment, avoiding the use of cumbersome equipment. The adoption of AR in an Industry 4.0 vision (Drath and Horch, 2014) has been proposed by Yew *et al.* (2016), with the aim to enhance the information perception of the different types of workers' interactions in the environment. Liu and Zhang (2015) and Rohidatun *et al.* (2016) have instead proposed AR solutions respectively for welder training and assembly/disassembly training.

Finally, two *trendy* research topics emerged for technical papers, i.e., calibration and ergonomics. Calibration of AR devices has been dealt with by Canessa *et al.* (2014) for the case of a color camera, Liu *et al.* (2016) for an AR guiding system, Kellner *et al.* (2012) for an HMD, and Eck *et al.* (2015), Itoh *et al.* (2015) and Moser *et al.* (2015) for OST-HDMs. Ergonomic issues were instead examined by Schega *et al.* (2014), who evaluated the effect of different HMDs on visual performance of the users, and Tuma *et al.* (2016) who used AR to evaluate the ergonomic state of a workplace.

3.2.4. Application papers

The analysis of the authors' keywords for the application papers lead to an original list of 304 different terms. As per the previous examination, three papers lacked the author's keywords or index keywords and where therefore excluded from this analysis. The general keyword "augmented reality" was also excluded from the analysis.

The original list of keywords was analyzed to identify possible similarities in the concept expressed and in the case group them; this screening reduced the keywords to 142. Results are proposed in Table 3, which, to be more effective, focuses again on keywords with a frequency of ≥ 2; keywords difficult to group were referred to as "non-grouped" keywords and clearly score a frequency of one each.

Table 3 shows that AR applications in industry have targeted the areas of assembly (6.05% of the grouped keywords), maintenance (4.84%), design (3.63%), and manufacturing (2.82%). Mobile applications (2.82%), 3D models (2.02%), and VR (2.02%) are the most relevant kinds of applications developed.

By correlating these findings with the analysis of the persistency of each keyword, which is again shown in Table 3, the research topics were classified as proposed in Figure 5. To build the graph in Figure 5, the horizontal line was set again at persistence =5.5, while the vertical line was set at frequency =3.6, which is the mean of the frequencies for the grouped keywords. From Figure 5 it can be seen that for application papers there are 10 *well-established* research topics relating, among others, to AR applications in the field of assembly, maintenance, design/prototyping, manufacturing, and order picking. Assembly turned out to be a well-established research topic for both application papers and technical papers; this means that numerous works have focused on either the development of hardware/software AR solutions for assembly or the deployment of AR to guide operators in assembly tasks. Application papers have focused, in particular, on this latter aspect (Pang *et al.*, 2006; Yuan *et al.*, 2008; Valentini, 2009; Ong & Wang 2011; Gonzalez-Sanchez *et al.*, 2012; Liu *et al.*, 2015; Wang *et al.*, 2016b); the same approach can be easily extended to the disassembly process, as done by Tegeltija *et al.* (2016). Zhang *et al.* (2011) have also integrated AR with Radio-Frequency IDentification (RFID) technology to guide operators in the assembly process. Product design issues are sometimes integrated with assembly issues, as both activities are critical to the product development process (Ng *et al.*, 2013). AR

Table 3. Frequency of keywords of the application papers and year of appearance.

Keyword	*Frequency*	*Persistency*	*Percentage (%)*	*Year of first appearance*
Assembly	15	11	6.05	2006
Maintenance	12	6	4.84	2011
Design	9	11	3.63	2006
Manufacturing	7	9	2.82	2008
Mobile	7	5	2.82	2012
3D	5	6	2.02	2011
VR	5	4	2.02	2013
Picking	4	8	1.61	2009
Collaboration	4	8	1.61	2009
Prototyping	4	8	1.61	2009
Bare-hand	4	6	1.61	2011
Building information modeling (BIM)	4	6	1.61	2011
Safety	3	5	1.21	2012
MAR	3	3	1.21	2014
Interaction	3	8	1.21	2009
HMI	3	7	1.21	2010
Quality control	3	7	1.21	2010
Training	3	4	1.21	2013
MR	3	7	1.21	2010
Camera	3	9	1.21	2008
Intelligent algorithm	3	3	1.21	2014
Learning	3	5	1.21	2012
Telematics	2	1	0.81	2016
Registration	2	7	0.81	2010
Object tracking	2	5	0.81	2012
Context-awareness	2	4	0.81	2013
Acceptance sampling	2	1	0.81	2016
Ergonomics	2	4	0.81	2013
User interface	2	6	0.81	2011
Haptics	2	7	0.81	2010
Real time	2	9	0.81	2008
Authoring	2	4	0.81	2013
Remote assistance	2	2	0.81	2015
Layout planning	2	4	0.81	2013
Spatial augmented reality (SAR)	2	2	0.81	2015
CAD	2	6	0.81	2011
Tracking	2	11	0.81	2006
Visualization	2	4	0.81	2013
User test	2	8	0.81	2009
Natural interface	2	4	0.81	2013
Marker	2	1	0.81	2016
Non-grouped keywords	*100*		*40.32*	

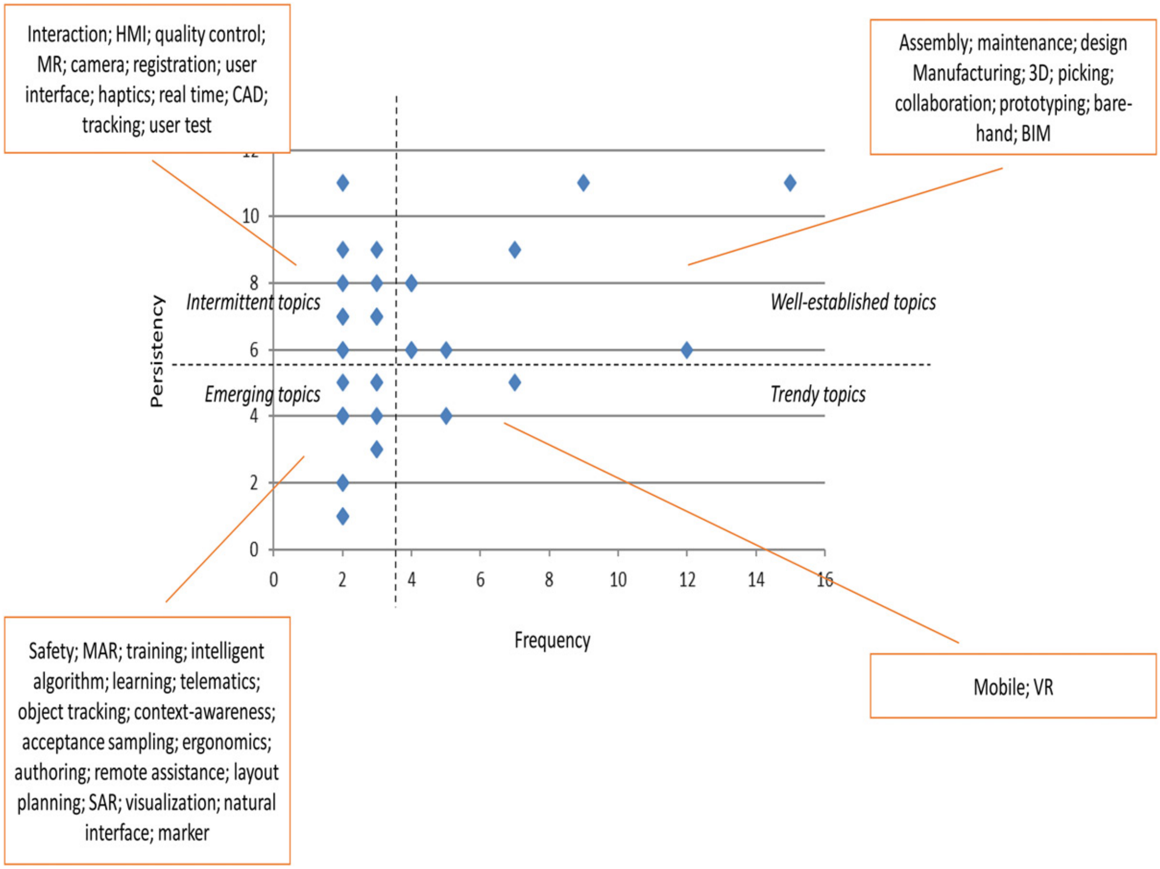


Figure 5. Persistence versus frequency of the keywords for application papers.

applications targeting expressively the product design issues have been carried out by Januszka and Moczulski (2011), Huang *et al.* (2012), Luh *et al.* (2013), Yang *et al.* (2014), Lee *et al.* (2009), and Lee, Lee, Kim and Kim, 2010). Maintenance is another well-established application area of AR technology; the purpose of AR deployment in this field could be either to train employees about maintenance tasks (De Crescenzio *et al.*, 2011; Webel *et al.*, 2013; Westerfield *et al.*, 2015), or to enhance the effectiveness and accuracy of the process, by supporting and guiding employees and avoiding errors or safety issues (Henderson and Feiner, 2011; Lee and Akin, 2011; Espíndola *et al.*, 2013; Ong and Zhu, 2013; Zhu *et al.*, 2013, 2014; Fiorentino *et al.*, 2016). AR is particularly useful in those situations where maintenance activities should be carried out in hazardous environments (De Crescenzio *et al.*, 2011; Martínez *et al.*, 2013; Nakai and Suzuki, 2016) or when the machine/device is complex (Golański *et al.*, 2014; Wójcicki, 2014). Three papers (Reif and Günthner, 2009; Reif *et al.*, 2010; Krajcovic *et al.*, 2014) have finally applied AR to improve the accuracy and efficiency of the order picking process. Among the technical aspects, bare-hand solutions have been implemented quite frequently in industry, especially in the field of assembly (Ong and Wang 2011; Ng *et al.*, 2013; Wang *et al.*, 2016c). “Bare-hand” means that no device has to be worn to interact with a computer; rather, the position of the hand and the fingers is used to control applications directly. These solutions can be interesting, as they do not need additional equipment or physical sensors, which can be inconvenient for employees and relatively inaccurate (Choi *et al.*, 2011).

Intermittent research topics of application papers include 12 themes, embracing AR applications for CAD, quality control, tracking or HMI. In the field of CAD, Januszka and Moczulski (2011) have adopted AR for aiding product designers in the development of machinery systems; Fiorentino *et al.* (2013) have instead proposed a design review workspace which acquires user motion using a combination of video and depth cameras and visualizes the CAD models using monitor-based AR. The use of AR for quality control has been proposed solely by Franceschini *et al.* (2016). Studies dealing with HMI have been developed by Lee *et al.*, (2010) and Tegeltija *et al.* (2016). The technical solutions that fall among the intermittent concepts embrace the use of haptic devices (Lee, Lee, Kim and Kim, 2010; Ferrise *et al.*, 2013; Webel *et al.* 2013) and the development of user interfaces (Henderson and Feiner, 2011; Golański *et al.*, 2014; Chen, Chi, Kang and Hsieh, 2016).

Emerging research topics (17) encompass AR usage for safety, learning, training, ergonomics, remote applications (remote maintenance in particular), and layout planning. The use of AR for occupational safety is a very recent topic. The rationale for adopting AR for safety purposes is that this technology can be useful in reducing some risk factors for work injuries, namely insufficient training or work experience and monotonicity of the tasks performed. More precisely, by guiding the employees step-by-step in their work, safety procedures can also be implemented successfully (Tatić and Tešić, 2017). As far as learning is concerned, AR has been adopted in e-learning (El Kabtane *et al.*, 2016) and mobile learning (Gonzalez-Sanchez *et al.*, 2012) environments. Vignais *et al.* (2013) have instead proposed an AR-based tool for the evaluation of ergonomic conditions of workers, with a particular attention on the potential risks for musculoskeletal disorders. Ng *et al.* (2013) have addressed ergonomic issues related to an AR-based assembly process. Remote applications with the use of AR have been proposed by Adcock and Gunn (2015), Gurevich *et al.* (2015), Mourtzis *et al.* (2017), and Neges *et al.* (2017). SAR and MAR are among the emerging technical solutions. SAR augments real-world objects and scenes without the use of displays such as monitors, HMDs or hand-held devices; instead, it makes use of digital projectors to display graphical information onto physical objects. MAR systems make use of one or more of the following tracking technologies: digital cameras and/or other optical sensors, accelerometers, GPS, gyroscopes, solid state compasses, RFID and wireless sensors (Chatzopoulos *et al.*, 2013). SAR has been applied to enhance the accuracy of automotive manufacturing processes (Doshi *et al.*, 2017). Examples of MAR usage in industry have been proposed by Shaaban *et al.* (2015) for the case of laptop maintenance and Monroy Reyes *et al.* (2016) for the training of students in the use of milling and lathe machines in laboratories.

Finally, the two *trendy* research topics of application papers embrace the development of mobile applications and VR applications. Kim and Moon (2013) have implemented a mobile application using AR to train employees in car maintenance. Tsai *et al.* (2012) have developed a mobile solution integrating AR and geographical information to help the evacuation of people in the case of a nuclear accident. VR applications have been proposed by Park and Kim (2013), Gavish *et al.* (2015), and El Kabtane *et al.* (2016) in the training environment and Tatić and Tešić (2017) in the occupational safety environment.

3.3. Field of application of AR

Some initial insights about the key application fields of AR systems have already been gained from the analysis of the grouped keywords proposed previously. To confirm these preliminary indications, the application field was analyzed across the different groups of papers and as a function of the publication year. The distribution of the application field across the four groups of papers is proposed in Table 4. As many papers typically mention a primary field of usage of AR and a secondary one, the total number of applications listed in Table 4 is higher than the number of studies reviewed.

From Table 4 it can be seen that 37 papers do not specify an application field for AR; these are mostly technical papers that developed either general AR solutions or conceptual/review papers that discussed the usage of AR under a general perspective without referring to a particular context. Apart from these studies, results in Table 4 confirm that assembly and maintenance are the most popular application fields of AR, as they are mentioned (either as the primary or secondary fields of usage of AR) in 15.09% and 14.65% of the papers, respectively. Moreover, all paper types have targeted these fields, although application papers and technical papers are obviously prevalent. The next most widespread fields of adoption of AR are training/learning (12.5% of the studies reviewed), product design (7.33%), safety (6.03%), remote assistance (5.17%), and telerobotics/robotics (5.60%). It is worth mentioning that some application fields are frequently considered together: this is, for instance, the case for assembly and training (eight papers), maintenance and remote assistance (seven papers), maintenance and training (seven papers), safety and ergonomics (three papers), assembly and product design (three papers).

Looking at the evolution of the application fields in time, Table 5 shows that the interest towards AR adoption in the field of assembly and maintenance has grown in time, with most of the papers (22 out of 35 for assembly and 23 out of 34 for maintenance) published between 2013 and 2016; this

Table 4. Field of application versus paper type.

Application field	*Application papers*	*Conceptual papers*	*Review papers*	*Technical papers*	*Total*
Assembly	15	6	3	11	**35**
Maintenance	23	2	2	7	**34**
Product design	11		2	4	**17**
Safety	8		1	5	**14**
Remote assistance	6	2	1	3	**12**
Telerobotics/robotics	1		3	9	**13**
Ergonomics	1	2	1	3	**7**
Training/learning	13	6	3	7	**29**
Quality control	3	1			**4**
Facility inspection or management	4				**4**
Outdoor environment	1			3	**4**
Picking	3			1	**4**
Diagnostic	3				**3**
Prototyping	1	1		1	**3**
Information	1	1	1		**3**
Navigation	1	1			**2**
2D/3D CAD	1		1		**2**
Layout planning	1				**1**
Welding	1				**1**
Machining simulation	1				**1**
Other		1		1	**2**
not specified		*4*	*4*	*29*	***37***

Table 5. Field of application versus year of publication (*Note: partial results for 2017*).

Application field	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*Total*
2D/3D CAD	1							1					**2**
Assembly	1	1	1	2	3	3	1	8	2	4	8	1	**35**
Product design	1	1	1	3	1	1	2	4	1	1	1		**17**
Diagnostic							1	1	1				**3**
Ergonomics		1			1			2	1		2		**7**
Facility inspection or management						1		1	2				**4**
Information					1				1			1	**3**
Layout planning								1					**1**
Machining simulation					1								**1**
Maintenance		1	2	1		3	1	10	5	4	4	3	**34**
Navigation												2	**2**
Training/learning			1	1	5	2	1	6	2	4	7		**19**
Telerobotics/robotics	3		1					2		3	4		**13**
Outdoor environment	1				1	1					1		**4**
Picking		1		1	1				1				**4**
Prototyping				1				1			1		**3**
Quality control					2				1		1		**4**
Remote assistance			2	1				2	1	5	1		**12**
Safety	1	2	1				2	2	1	1	3	1	**14**
Welding												1	**1**
Other						1				1			**2**
not specified	*1*	*1*	*3*		*3*	*3*	*4*	*3*	*4*	*9*	*5*	*1*	***37***

Table 6. Industrial sector versus paper type.

Industrial sector	*Application paper*	*Conceptual paper*	*Review paper*	*Technical paper*	*Total*
Aircraft	3				**3**
Architecture, engineering, construction and operations (AECO)	5	1		5	**11**
Automotive	6	2		3	**11**
Chemical plants	1				**1**
Electronics	4	2			**6**
Food industry			1		**1**
Footwear	2				**2**
Laboratory	23	6	3	49	**81**
Machine tool	7	3		2	**12**
Manufacturing	9	2	3	4	**18**
Warehousing	4				**4**
Nuclear/power plants	4				**3**
Other	1	1		1	**3**
not specified	*1*	*3*	*8*	*5*	***17***

suggests that these fields of application of AR, although quite explored, are still attracting new research. Similar considerations can be made for AR adoption for training/learning purposes. Safety, telerobotics/robotics, and remote assistance, instead, are application fields of AR which have emerged in recent years and are now investigated with good continuity.

Further indications can be derived from an analysis of the industrial sector of interest for the implementation of AR. In this case, we have not considered the main area of application of the AR solution, as done previously, but instead focus on the industrial sector where the application was developed and implemented (e.g., automotive sector, oil & gas sector, etc.). The results of this analysis are shown in Table 6.

Table 6 shows that in most cases (81 out of 174 papers, 46.55%) the system's implementation was carried out in laboratory settings, which prevents the possibility of identifying a particular industrial sector. Most of the times this is the case for technical papers (49), as it was reasonable to expect. Any AR solution, however, is ultimately expected to leave the lab and be used in the real industrial context (Georgel, 2011); in this respect, laboratory studies typically represent a proof-of-concept of the AR applicability and should be seen as the first step for the development of a scalable solution.

Among studies developed in a particular sector, the manufacturing (10.34%), machine tool industry (6.90%), AECO (6.32%), and automotive (6.32%) industries are the most popular contexts where AR has been implemented. Other sectors, which are less frequent among the studies reviewed, are the aircraft, chemical, food, footwear, and electronic industries, the warehouse processes and nuclear/power plant sector. Probably, the cost-effectiveness, benefits, and scalability of AR solutions in these contexts has still to be demonstrated (Weidenhausen *et al.*, 2003).

By examining jointly the industry sector and *primary* field of usage of AR (where specified), it is easy to see that most implementations of AR for assembly were carried out in laboratory settings or targeted the machine tool industry (Table 7). AR studies in the manufacturing industry, instead, have primarily focused on maintenance or product design issues. It is interesting to note that AR studies targeting ergonomics issues have been entirely carried out in laboratory settings, with real case applications still lacking in the literature.

Table 7. Industrial sector versus primary application field of AR.

	Aircraft	AECO	Automotive	Chemical plants	Electronics	Food	Footwear	Laboratory	Machine tool	Manufacturing	Nuclear/power plant	Warehousing
2D/3D CAD								1				
Assembly	1		3		2			17	4			
Diagnostic										1		
Ergonomics								4				
Facility inspection or management		1								1		
Information						1						
Layout planning										1		
Training/learning			1					9	1	1		
Machining simulation								1				
Maintenance	2	2	3		1			8	3	4	1	
Navigation		2										
Outdoor environment		3										
Picking								1				3
Product design			1		1		2	4	1	3		
Quality control			1							1		1
Remote assistance			1		2			2	2			
Safety		3		1				2			3	
Telerobotics/robotics								8		2		
Welding			1									
Other								1				

3.4. Technology evolution

We now examine the technological solutions adopted in the implementation of AR systems. According to Reif *et al.* (2010) and Jeon *et al.* (2010), a typical AR system includes some essential components, such as the visualization/capturing device, the interaction device, and the tracking system. Capturing technologies are technological solutions adopted to capture a scene, which can then be viewed by a user with superimposed information. These technologies are therefore responsible for collecting information about the environment. Visualization devices are used to display the results of image processing or the image of the real-world enriched with additional useful information (Milgram and Kishino, 1994). Interaction devices are used for commands that affect information processing and displaying. Finally, tracking technologies typically refers to the technological solutions used to enable the AR system to recognize the key components in the captured scene and thus provide the correct information when augmenting the scene itself. Tracking technologies are also essential for identifying the user's position within the industrial environment.

Most of the papers reviewed describe all the components of the AR solutions; however, some papers describe more than one AR application (and thus the hardware components are more numerous) whereas other papers (in particular, technical papers, review papers or conceptual papers) do not always focus on the description of the full AR architecture. Consequently, the number of solutions described below does not reflect the number of published studies.

Table 8 provides an overview of the technological solutions as a function of the paper type, whereas Table 9 describes the evolution of these technologies over time. From these tables it is easy to see that "camera," or its variant "camera connected to a monitor," are the most commonly used solutions for capturing the scene of the external environment; in that case, the monitor displays the scene to the users with the relevant additional information. Another technological solution frequently adopted for visualization purposes is the HMD. Compared with the first solution, the HMD is easier to transport and does not require cameras or monitors to be installed in the production area. The use of HMD solutions has slightly increased in time: since 2011, more than six papers per year make use of this solution. However, some authors have recently criticized the use of HMD, especially for remote assistance purposes (Gurevich *et al.*, 2015); as a matter of fact, the use of HMD could force the worker to limit his/her head movements in an attempt not to make the view of the remote assistant unstable. Some studies also reported that users can suffer from decreased visual acuity while looking at a physical target through HMDs (Livingston *et al.*, 2005).

In studies published since 2010, most of the technological solutions for visualization make use of tablets, smartphones or other mobile devices, e.g., ultra-mobile PCs. In this case, the scene is captured by the device camera and is immediately visualized with superimposed information on the device display. Compared with HMD solutions, the use of tablets or smartphones is more socially accepted and has the advantage of being even easier to transport. However, mobile devices are hand-held when used, which can hinder the operator when he/she has to carry out manual tasks (e.g., assembly or maintenance tasks). For this reason, bare-hand solutions have been proposed, starting from 2011. These solutions aim at developing a natural and intuitive hand-based interaction with virtual objects and have been applied in seven papers; moreover, as this is a relatively new interaction technique, five papers have investigated bare-hand interaction from a technical point of view.

In some of the papers reviewed, non-conventional AR systems were developed. Jimeno-Morenilla *et al.* (2013) provided an example of use of a non-conventional system, i.e., an infrared emitter coupled with a pair of active glasses.

Table 8. Technological devices versus paper type.

Visualization, capturing and interaction devices	*Application paper*	*Conceptual paper*	*Review paper*	*Technical paper*	*Total*
3D scanner	1			1	**2**
Bare-hand	7			5	**12**
Camera	31	1	1	37	**70**
Camera connected to a monitor	10	3		3	**16**
Display	4	2	1		**7**
Haptic devices	5	1	1	8	**15**
Head-worn camera	2			3	**5**
HMD	28	8	6	20	**62**
Holographic display				1	**1**
Inertial measurement unit	1			2	**3**
Infrared machine				1	**1**
Laptop	5	2		5	**12**
Projector	5	2		5	**12**
Tablets, smartphone or other mobile devices	25	3	7	16	**51**

Table 9. Technological devices versus year of publication (*Note: partial results for 2017*).

Visualization, capturing and interaction devices	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*Total*
3D scanner	1						1						**2**
Bare-hand						1	1	4			6		**12**
Camera	4	2	4	2	7	6	1	9	8	8	15	4	**70**
Camera connected to a monitor				2	1	1		5	2	1	4		**16**
Display			1		1	1		3			1		**7**
Haptic devices	1	1		1	2		1	3	1	3	2		**15**
Head-worn camera	1				1	1		1		1			**5**
HMD	3	2	5	3	5	8	5	7	7	8	6	3	**62**
Holographic display								1					**1**
Inertial measurement unit		1						2					**3**
Infrared machine								1					**1**
Laptop					1	1	2	2	3	1	1	1	**12**
Projector							1		1	3	5	2	**12**
Tablets, smartphone or other mobile devices	1	2	3	2	3	2	3	8	7	6	10	4	**51**

Table 10. Technological device versus primary application field of AR.

Application field	*3D scanner*	*Bare-hand*	*Camera*	*Camera connected to a monitor*	*Display*	*Haptic devices*	*Head-worn camera*	*HMD*	*Infrared machine*	*Laptop*	*Projector*	*Tablets, smartphone or other mobile devices*
2D/3D CAD								1				
Assembly		4	9	4				5		1		5
Product design	1	2	5	3				2				2
Diagnostic				1				1		1		
Ergonomics		1						4				1
Facility inspection or management			1					1				1
Information												1
Layout planning			1									
Training/learning			4	3	2	4		6		2		2
Machining simulation								1				
Maintenance			7	1		1		7				12
Navigation			1					1				
Outdoor environment			1				1					2
Picking						1		3				
Telerobotics / robotics		1	6					2				2
Prototyping								1	1			
Quality control			2					1				1
Remote assistance			4		2			1				3
Safety			2					1			1	6
Welding			1									

Similarly, Liu *et al*. (2013) described a technical issue of AR systems equipped with holographic displays.

By coupling the technological solution with the *primary* application field of usage of AR (where specified), we got the results shown in Table 10. This table shows that cameras, HMDs and tablets/smartphones have been adopted in almost all application fields of AR. The use of HMDs and mobile devices is slightly prevalent in the areas where instructions should be given to the user, i.e., assembly and maintenance. This is consonant with the fact that HMD instructions are more effective than paper instructions (Tang *et al*., 2003) and that the use of mobile devices decreases the risk of errors in assembly operations. Bare-hand solutions instead have been primarily adopted in the (augmented) assembly process, probably because assembly is a manual process where ergonomic issues cannot be ignored (Azuma, 1997; Wang, Ng, Ong and Nee, 2013).

Tracking systems for AR can be classified into two main categories, namely "marker-based tracking" and "marker-less tracking (Ababsa *et al.*, 2010). The analysis of the selected papers (Table 11 and Table 12) reveals that marker-based systems are the most frequently adopted solutions, as they are mentioned in 89 out of 174 papers reviewed (51.1%) and of 125 papers (71.2%) that expressively describe the tracking solutions adopted. Marker-based solutions have been implemented in both older and more recent studies, with an increase in usage in the last years. In these systems, a kind of tag is placed on the elements of interest, to allow the AR system to recognize it and provide the related information when required. The studies analyzed made use of barcodes/QR codes (two papers), fiducial markers (14), optical markers (25), physical markers (11) or RFID tags (three) to this end.

Marker-less systems are mentioned in 36 out of 174 studies reviewed (20.7%). When marker-less systems are adopted, several different solutions can be used to track the elements of interest. For instance, Zhang *et al.* (2010b) developed a hybrid tracking method combining area-based and feature-based tracking, whereas De Crescenzio *et al.* (2011) adopted feature tracking: the application recognizes a particular feature, which acts as a marker. Koch *et al.* (2014), Fiorentino *et al.* (2016), and Neges *et al.* (2017) made use of natural markers, i.e., markers that are already available on-site and that because of their particular shape or color have great potential to be used for optical tracking.

3.5. Results of the AR implementation

As discussed in the previous sections, most of the papers reviewed have developed an AR application that could help operators carry out tasks typical of industrial procedures. According to Georgel (2011), the fact that the system was tested is one of the key evaluation criteria for assessing AR solutions. For the purpose of this study, we distinguish between AR systems that have been "not tested," "technically tested" (i.e., tested only in terms of technical functioning) or "user tested," that is tested with a group of users, to evaluate user acceptance and performance. Out of the 174 studies reviewed, 139 papers have carried out either a technical test or a user study. Looking at the application papers, most of them (32 out of 70, 45.7%) carried out a user study to evaluate the benefits generated when AR systems (instead of traditional methods) are used to assist the user in the execution of a task; in addition, 28 papers (40.0%) propose a technical test of the developed application, aimed at illustrating how it functions (Table 13). The majority of technical papers (45 out of 69, 65.2%) carried out a technical test aimed at assessing the functioning of the technical solutions developed; conversely, user studies are more limited in number (18 out of 69, 26.1%). User tests were conducted also in 12 conceptual papers and one review paper.

As far as the results observed are concerned, obviously many studies measured more than one outcome generated by the AR implementation. The distribution of the results observed as a function of the type of test carried out (either user studies or technical tests) and paper classification (Table 14) shows that technical tests are mainly intended to evaluate the effectiveness of the technical solutions, which is mentioned among the test results in 54 out of 66 cases (81.8%). Technical papers contribute mainly to this outcome, with 34 studies that have tested the effectiveness of the solution developed. Looking at the papers that carried out user studies, their focus is primarily on evaluating the savings in the time required to carry out a given task: this is assessed in 26 cases out of 102 (25.5%). Further outcomes frequently measured in user studies are again the performance of the technical solution, in terms of its effectiveness and ease of usage (reported in 23 and 20 cases, respectively) and the possibility of reducing errors associated with the task executed (16 cases).

By combining the results observed through user studies or technical tests with the *primary* application field of AR (where specified), we found that assembly and maintenance can benefit from faster execution of activities to the greatest extent (Table 15). Better training is the typical result for AR application targeting learning/training issues. Testing the effectiveness of the solution developed is an important aspect of many application areas of AR, including assembly, maintenance, product design, and telerobotics/robotics.

Table 11. Tracking technology versus paper type.

Classification	*Marker-based tracking system*	*Marker-less tracking system*
Application paper	42	19
Conceptual paper	7	3
Review paper	8	1
Technical paper	32	13
Total	*89*	*36*

Table 13. Test of the AR system versus paper type.

Classification	*Test type*	*Total*
Application papers	user test	32
	no test	10
	technical test	28
Conceptual papers	user test	12
	no test	6
	technical test	2
Review papers	user test	1
	no test	14
Technical papers	user test	18
	no test	6
	technical test	45

Table 12. Tracking technology versus year of publication (*Note: partial results for 2017*).

Year of publication	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*Total*
Marker-based tracking system	3	1	4	4	8	7	3	15	8	14	17	5	**89**
Marker-less tracking system	2	1	3		2	1	5	4	6	3	7	2	**36**

Table 14. Study results versus paper type.

	Results observed								
Type of test and paper classification	*Better training*	*Enhanced safety conditions*	*Error reduction*	*Faster execution of activities*	*Level of adoption*	*Performance improvement*	*Reduced workload*	*Solution effectiveness*	*Usage satisfaction*
Technical test	*1*		*4*	*1*		*1*		*54*	*5*
Application paper	1		4	1		1		18	3
Conceptual paper								2	1
Technical paper								34	1
User test	*8*	*3*	*16*	*26*	*1*	*4*	*1*	*23*	*20*
Application paper	4	3	8	13		3		10	12
Conceptual paper	3		5	6	1		1		3
Review paper				1				1	
Technical paper	1		3	6		1		12	5
Total	*9*	*3*	*20*	*27*	*1*	*5*	*1*	*77*	*25*

Table 15. Study results versus primary application field of AR.

	Result observed								
Application field	*Better Training*	*Error reduction*	*Faster execution of activities*	*Improved working conditions*	*Performance improvement*	*Reduced workload*	*Solution effectiveness*	*Usage satisfaction*	*Total*
Assembly	1	2	7				11	2	23
Diagnostic									0
Ergonomics		1	1			1		1	4
Facility inspection or management	1						1	1	3
Information									0
Layout planning							1		1
Learning/training	7	2	2	1			4	1	17
Machining simulation							1		1
Maintenance		3	5		3		8	4	23
Navigation							2		2
Outdoor environment							3		3
Picking			2				1		3
Product design							7	4	11
Prototyping								1	1
Quality control			1				2		3
Remote assistance		1	2				1	2	6
Safety		1	3				2	2	8
Telerobotics/robotics			1				5		6
Welding							1		1
Other			1				1		2

Among the studies that carried out a thorough assessment of the benefits generated by AR applications, De Crescenzio *et al.* (2011) presented a prototype based on an AR system to help operators in executing maintenance tasks on aircraft. Their proposed system was tested with 10 operators, who showed improved performance and satisfaction when using the prototype. Operators were asked to evaluate the system; workload, performance and usage satisfaction were all judged positively. Webel *et al.* (2013) presented an AR system that can be used to train and guide technicians through complex assembly and maintenance tasks. The application has been tested at Sidel. The results obtained with this application showed that AR had a positive impact on the execution of maintenance tasks: technicians equipped with the application required 14% less time to complete the assigned job. The average number of unsolved errors scored 0.30 for equipped operators, whereas for unequipped ones it scored 1.30. The only drawback was that employee training time increased by 20% when the AR application was adopted. The subjects involved in the test were the same age and had equivalent work experience. AR also shows potential for operations requiring remote assistance. For instance, Gurevich *et al.* (2015) developed a remote video collaboration system called "tele-advisor" that allows a remote expert to naturally guide a local user in need of assistance in carrying out physical tasks around real-world objects. The system was tested on 24 users, four of which acted as remote helpers and 20 as local users. The participants perceived the prototype of tele-advisor as having good potential for making daily tasks easier and faster to complete; moreover, most users, both acting as helpers and workers, were able to easily understand how to use the system. Looking at different areas of implementation, Reif *et al.* (2010) have tested their prototype of "pick-by-vision" system on 16 order pickers, by evaluating the time required to complete the task (i.e., 14 picking lists) and the number of errors made; a qualitative evaluation of usability, impression and cognitive load resulting from the use of the tool were also measured with questionnaires.

4. Discussion and conclusions

The objective of this study was to carry out a literature analysis is to examine current state-of-the-art of AR technology and highlight its key benefits within the industry. In line with the aim of the analysis, several search queries were made on three scientific databases and led to the identification of 174 studies published from 2006 to early 2017 and focusing on AR in industrial environments. These studies were classified into review papers (15), conceptual papers (20), technical papers (69), and application papers (70). The whole sample of papers was analyzed through descriptive statistics about the year of publication and geographic origin of the study. Next, review papers and conceptual papers, which are less numerous, were examined individually; application papers and technical papers instead were analyzed by classifying the study keywords, which led to the identification of the main topics explored and to their level of diffusion in the scientific community. Further analyses, targeting the field(s) of application of AR, the technology evolution, and the main result(s) generated from the AR adoption, were then made on the overall sample of papers, to validate the outcomes from the preliminary examination.

From the overall set of analyses made, the following considerations emerge. First, interest towards the use of AR technology in industrial operations is increasing over time, as highlighted by the growing number of recent papers focusing on AR usage in industry. In relation to the geographical origin of the studies, it has been noticed that most of the papers reviewed are from Singapore, Germany, Italy, and USA; many countries, instead, have carried out less than two studies on AR from 2006 to 2017, demonstrating that this technology is still in its early stage of adoption.

Some specific application fields of AR seem to have been investigated in detail, with both application papers and technical papers that targeted these topics; this is the case for assembly, maintenance, product design, and training/learning. Other interesting application fields (such as safety, ergonomics or remote collaboration) have emerged recently; although they are now investigated with good continuity, the number of studies found is still limited and suggests that the potential of AR in these contexts has not yet been fully explored.

Looking at the industrial sectors where AR has been used, it is not yet easy to identify a particular sector that can gain greater benefit from AR technologies. The majority of the application papers either focused on the general context of the manufacturing industry or on the machine tool industry. However, many technical studies were carried out only in laboratory settings, without implementing the AR system in a real context; as a consequence, real case implementations lack for AR solutions targeting specific areas, e.g., ergonomics. As AR solutions are ultimately expected to be used in real industrial contexts (Georgel, 2011), further research activities should be undertaken for the development of scalable AR solutions in less explored areas.

Other aspects often debated in literature are technical and technological issues relating to the development and implementation of AR systems intended for the industrial context. Many papers (technical papers and application papers in particular) detail the tracking technologies, visualization technologies, and rationale behind the choice of such technological solutions. In most of the studies reviewed, the technological solutions for visualization either use mobile devices (such as tablets, smartphones or ultra-mobile PCs) or HMDs. This is probably the consequence of the reduced cost of these devices. In addition, tablets or HMDs are more easily transportable and usable by the employees and more likely to be implemented in these contexts. However, mobile devices are handheld when used, which can hinder the operator when he/she has to carry out manual tasks (e.g., assembly or maintenance tasks, which are frequently the focus of AR applications). In addition, HMDs have been criticized for adoption because their use can generate ergonomics problems (Livingston *et al.*, 2005; Gurevich *et al.*, 2015). Other technologies (e.g., bare-hand solutions) have therefore emerged for developing a natural and intuitive hand-based interaction with virtual objects. Overall, from a practical point of view, these results suggest that the choice of the device to implement ultimately depends on the application field of the AR system. Looking at the tracking technology, marker-based solutions are usually preferred, probably because of the better accuracy compared to marker-less solutions and ease of implementation.

Most of the published papers have evaluated the benefits that AR systems can generate in industrial operations, compared with traditional techniques, by means either of user studies or technical tests. Whenever a quantitative analysis is performed, it shows that there are interesting advantages from AR applications in terms of decrease in the time required to complete a given task and in the number of errors per employee; a positive impression about the AR solution (either in terms of effectiveness, intuitiveness or ease of usage) is also observed frequently.

To sum up, from the discussion above it can be concluded that AR shows great application potential in many industrial operations, and in particular, in the field of maintenance and assembly. Moreover, it has been proven to be helpful also in different (less explored) areas such as remote assistance, training/learning, facility management or inspection and product design.

From a scientific perspective, as any review study this article does not present new research results; rather, its contribution comes from consolidating existing information from many recent studies that discussed AR solutions for the manufacturing industry. This complements previous research in AR systems, which mainly targeted the construction industry, by exploring a different application area of these systems: moreover, it is the logical prosecution of the previous review of AR in manufacturing (Ong *et al.*, 2008), that has analyzed studies published up to 2005. In addition, this review provides the reader with a good overview of the state-of-the-art of AR adoption in the manufacturing industry, highlighting well-established applications areas and promising application fields. From a more practical perspective, this review also identifies the main technological solutions (primarily in terms of visualization and tracking devices) that can be used for the development of an AR system in the manufacturing context. Their analysis provides interesting insights for companies wishing to implement AR solutions. Looking at the limitations of the study, a weak point is that we decided to exclude the construction sector from the analysis, in light of the fact that Behzadan *et al.* (2015) have recently carried out a review of AR applications in this specific field. This decision, although reasonable, led to the exclusion of a significant number of applications.

On the basis of the findings from this review, future research activities can be directed towards various points that have been treated only marginally in the papers reviewed. First, there is the need for exploring in greater detail the industrial sectors where AR systems could be successfully deployed. To this end, attention should be directed in particular to the application areas that were highlighted as “emerging” or “trendy” research topics as a result of the keywords analysis, e.g., training/learning, ergonomics/safety, maintenance and remote maintenance, facility layout and production management. Second, although the benefits of AR adoption have been evaluated in many studies, designing and implementing an AR system also involves significant costs (Azuma, 1997; Georgel, 2011; Vignali *et al.*, 2018). Therefore, an economic assessment of the costs and savings generated by the AR implementation is required. To this end, the development of the AR solution should be regarded as an investment, meaning that once implemented, its usage will continue for some years; hence, investment evaluation is probably the most appropriate approach to assess whether and how fast the invested funds return. Obviously, carrying out such evaluation and generalizing the resulting outcomes require a good number of AR applications in the next years. Finally, a third aspect to explore in future research activity is evaluating the manufacturing industry’s interest towards and knowledge of the use of AR solutions to enhance the performance of its processes. This analysis should possibly target those countries for which a very limited number of applications of AR solutions was found. Exploring interest towards AR solutions and the level of knowledge of these solutions can be done, for instance, by means of empirical analyses, such as questionnaire surveys, targeting manufacturing companies operating in the countries mentioned. Whenever interest in AR application is observed, a further point to explore concerns the specific fields of application (e.g., logistics, production and facility management, quality and safety, or maintenance) that are perceived to be promising for AR implementation. This can again be done by means of empirical research.

Funding

This research was funded by INAIL (Istituto Nazionale per l’Assicurazione Contro gli Infortuni sul Lavoro), the Italian National Institute for Insurance against Accidents at Work, under the project “W-Artemys” (Wearable augmented reality for employee safety in manufacturing systems) - BRIC ID38.

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