Mobile Networks and Applications (2024) 29:119–132
https://doi.org/10.1007/s11036-023-02121-x

Implementation of Augmented Reality in Smart Engineering Manufacturing: Literature Review

Jozef Husár[1] · **Lucia Knapčíková**[1]

Accepted: 13 January 2023 / Published online: 28 February 2023

Abstract

Nowadays, we are in the period of the 4th industrial revolution, which has had a great impact on many areas. Four industrial revolution started in 2011 when this term was introduced at the Hannover Market. One of the components of Industry 4.0 is Augmented Reality (AR). The literature review was based on articles indexed by the Web of Science database, published between 2011 and 2021, and focused on implementing AR in the industry. The literature review consists of an overview, technical, application, and conceptual articles. After the analysis, we focused on the areas of AR mobile implementation in industry, technological development, and the main results created by the AR application. The advantage of this manuscript is helpful for academicians and industry as it presents the current state of the art and guides steps for designing and analyzing the AR applications created.

Keywords Augmented reality · Industry · The mobile display device

1 Introduction

The article aims to provide insight into augmented reality (Augmented Reality), henceforth AR, in engineering production. We will focus on areas in manufacturing where previous research was needed on how AR has been implemented in the manufacturing industry in general and where it has been implemented the most, and what areas of its application are still unexplored. The term augmented reality is used to refer to a combination of technologies that allow realtime mixing of computer-generated content with live video displays. AR is based on techniques developed in virtual reality (VR) and interacts not only with the virtual world but is somewhat connected with the real world [1]. It is projection or adding a layer of digital content to a real physical environment in realtime. Augmented reality integrates digital components through applications on mobile devices into the real world, and digital content is visible through special AR glasses or using a tablet/smartphone, stationary screens, projection devices and other technologies [2]. The manufacturing industry is one of the leading areas of AR applications. Due to complex internal processes and the increasing globalization of supply chains, manufacturing companies need realtime information exchange at different stages of the product life cycle, i.e. j. design, prototyping, manufacturing, assembly, maintenance/repairs, etc. AR can be of great help in this area due to its ability to simulate, assist and improve processes even before they are carried out [3]. Virtual objects display information that the user cannot directly detect with his senses; information provided by virtual objects can help the user perform most tasks related to the product. AR applications for the manufacturing industry have been developed for several purposes, including process monitoring and control, plant and machine maintenance, product design and development, training programs, assembly, plant and building construction, and increasing industrial safety [4].

Moreover, the rapid development of mobile technologies promises to revolutionize mobile AR applications in the manufacturing industry. The primary focus of this research will be on AR applications in the manufacturing industry. Review articles, technical articles (articles whose

✉ Jozef Husár
jozef.husar@tuke.sk

✉ Lucia Knapčíková
lucia.knapcikova@tuke.sk

[1] Faculty of Manufacturing Technologies with the seat in Prešov, Department of Industrial Engineering and Informatics, Technical University of Košice, Bayerova 1, 080 01 Prešov, Slovak Republic

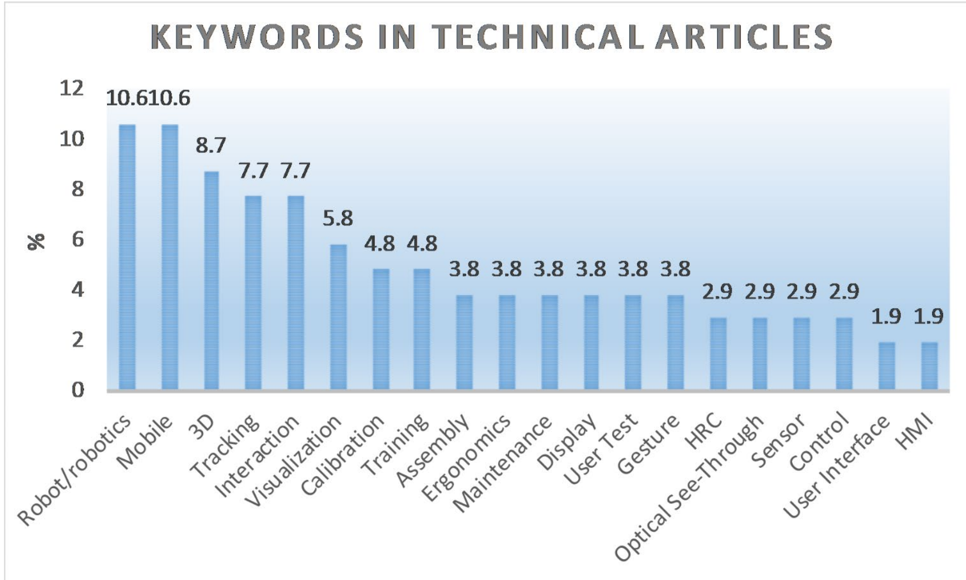

Fig. 1 Most used keywords in technical papers

main focus is the development or improvement (and possibly testing) of the technical hardware or software function of the AR system), application articles (works whose main focus is the development and possibly testing of an AR solution) in a real or laboratory environment) and concept papers (papers that do not develop a new AR solution or apply an existing AR system, but rather discuss some specific aspects or issues of AR adoption in the industry) published between 2011 and 2021, to answer the following questions:

What is the current status of AR in the manufacturing industry?
What AR applications are the most explored/promising/popular?
What is the "research gap" in this topic, and what will be my future research direction?
What are the key methodological approaches?
The future direction in the topic "augmented reality and its implementation in production" will be chosen based on the results.

2 Literature Review

2.1 Overview Articles

Prehľadové Review articles summarise existing literature on various aspects of AR solutions and applications. These articles propose general analyzes of the state of AR, focusing on major patents and AR in a manufacturing context [3]. Other studies investigate AR systems that can be used for specific purposes, such as improving human-computer interaction (HCI) [5] or human-robot collaboration (HRC) [6]. Several articles analyze AR applications dedicated to a specific industrial task; the most researched tasks are assembly [7, 8], maintenance [9–11], design [12, 13], safety/ergonomics [14] and food logistics [15].

2.2 Technical Articles

The 80 professional papers written between 2011 and 2021 were analyzed. They were analyzed based on the key-words used in these articles. The focus is on keywords that are used in two or more articles. The results are shown in Fig. 1.

Figure 1 shows that the most relevant research problems of technical works focus on robots (10.6%), mobile devices/applications (10.6%), 3D (8.7%), tracking (7.7%), interaction (7.7%),

visualization (5.8%), calibration (4.8%), displays (3.8%), user tests (3.8%), gestures (3.8%), optical clarity (2.9%), sensors (2.9%) and user interface (1.9%). As for the areas of use, the developed technical solutions were primarily focused on training (4.8%), assembly (3.8%), ergonomics (3.8%), maintenance (3.8%), human cooperation and robot (2.9%), control (2.9%) and interaction man-machine (1.9%).

From Fig. 1, it is clear that for technical articles, there are several well established research topics related to robotics, 3D, tracking, interactions, visualizations, implementation of AR in assembly, and development of mobile solutions or user interfaces. From this list, it can be seen that some keywords (e.g. "tracking" or "interaction") actually describe very general concepts or a common technical problem in the development of AR solutions, so researchers are likely to mention them more often. The use of AR for assembly is primarily motivated by the fact that, on the one hand, assembly processes constitute a significant part of the cost of the product [15–17]. On the other hand, these costs can be dramatically reduced if the product is assembled according to a well-planned assembly sequence. AR is therefore used for this purpose in an attempt to automate the process and increase its efficiency. However, some recent papers (publis-hed since 2019) provide some interesting solutions, such as a realtime vibrotactile guidance method that potentially overcomes existing visual problems [18], a combined hardware/software solution that provides an assistance system to identify assembly errors, and product repair [19] or a hardware/software architecture that assists operators involved in manual assembly processes in realtime and has been tested in practice [20]. Technical articles also address topics related to object recognition problems caused by the specific shape of products [16, 21] or automated placement of 3D objects in an assembly system [22]. Product design is another well-established area of AR adoption; in this context, AR is usually used to customize a product [23, 24], or to interact with its (virtual) 3D components [25].

The development of the user interface for AR solutions was dealt with by Caruso et al. [25], Ajanki et al. [26], Benbelkacem et al. [27] and Ludwig et al. [28]. The development of mobile AR solutions was discussed by Mourtzis et al. [29], whose work focused on customer integration in product personalization and they proposed the design of manufacturing networks on the go, through the development of applications for Android devices, and that application was tested in the automotive industry; Verbelen et al. [30] presented a cloudlet platform; Han and Zhao [31] developed a CAD-based method for recognizing 3D objects in monocular images, and their method attempts to estimate the position of a 3D object in the camera coordinate system; Kim and Lee [32] proposed a new method to directly manipulate 3D objects in AR through touch and hand gesture-based interactions in portable devices; Shatz et al.[33] developed a technology that enables the exchange of information between multiple transmitters and multiple receivers using optical data transmission in free space; Chen et al. [34] developed a technology that enables the exchange of information between multiple transmitters and multiple receivers using optical data transmission in free space. Their work provides insights for software and hardware designers to improve augmented reality workloads on mobile platforms. Other technical paper research topics include AR applications for maintenance and telerobotics and technical issues such as developing visualization systems or sensors. Devices used in this category include HMDs, cameras, and haptic devices. Maintenance is a key process for equipment and machinery to prevent breakdowns and is often performed manually, which requires considerable time and cost [35]. Maintenance represents an interesting problem area for the application of AR: in fact, most repair activities are performed by trained personnel who apply established procedures that can be efficiently organized into task sequences focused on a specific object, machine or location [36]. According to these arguments, in this area, AR technical solutions mainly focus on supporting inspectors during field in-spection/machine diagnostics or when performing maintenance [37], which also includes equipment maintenance [38]. AR is expected to avoid delays and possible errors during maintenance, thus reducing the associated costs [27]. Visualization issues were addressed by Stylianidis et al. [39]. They proposed the LARA project, which uses AR technology to provide accurate location of geolocated assets and new information visualization approaches in AR to address the specifics of hidden objects. HMD (head-mounted display) is a headset (special glasses) that contains two stereoscopic displays (for each eye separately) to generate images that the user perceives as three-dimensional; Weng et al. [40] performed an exhaustive review of display systems (including HMDs) suitable for AR. Kellner et al. [41] addressed the problem of calibrating these devices for optimal use in AR and VR environments. Haptic AR systems (also called visual-haptic augmented reality) allow users to see and touch digital information embedded in the real world. These systems have also been investigated by various researchers [42]. Arbelaez et al. [18] thus developed a Haptic AR application with a low-cost configuration to evaluate the support of the vibrotactile guidance method in real time based on the Gestalt continuity principle. This application potentially overcomes the existing visual problems of AR and allows the user to focus on the task at hand and avoid overreliance on technology.

Other research topics include the analysis of body tracking technologies (e.g. eye tracking, finger or gesture detection), optical technologies (mainly OST-HMD (Optical see-through) or handheld technologies (English handheld technologies). OST-HMD is a wearable device that can reflect the projected image and, at the same time, allows the user to see through it using AR. Moser et al. [43] investigated the technology of eye movement tracking and OST- HMD. They conducted a user study to evaluate the registration accuracy produced by three OST-HMD calibration methods from both objective (quantitative) and subjective (qualitative) perspectives. Similarly, Orlosky et al.[44] proposed ModulAR, a hardware and software application framework designed to improve the flexibility and handsfree control of transparent AR displays; the framework integrates eye tracking to control ondemand vision extensions such as optical zoom or extension field of view. Regarding gesture tracking, Kim and Lee [32] proposed a method to naturally and directly manipulate 3D AR objects

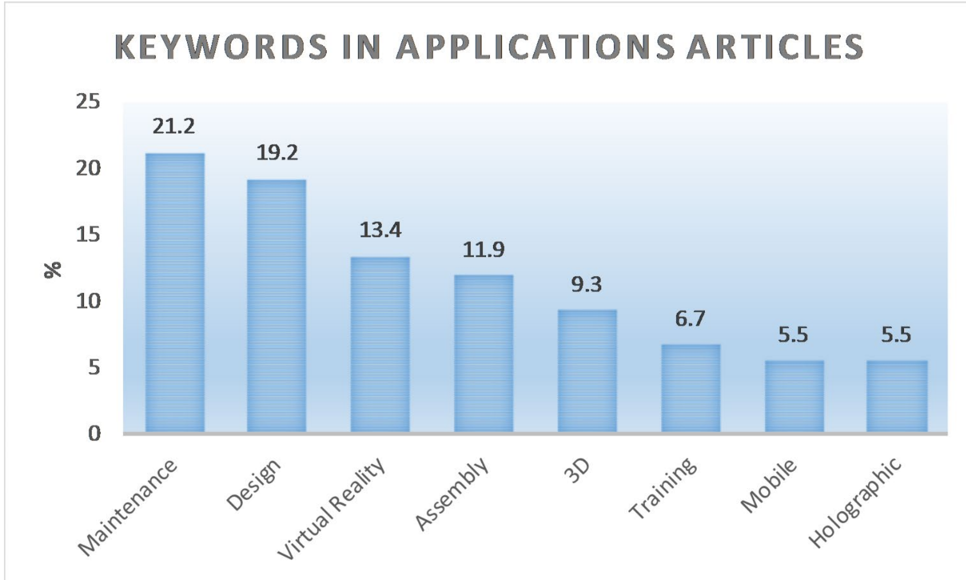

Fig. 2 Most used keywords in application articles

through touch and hand gesture-based interactions in handheld devices; a touch gesture is used to select an AR object, while a natural hand gesture allows for direct and interactive manipula-tion of selected objects. Lambrecht et al. [45] used a similar approach, i.e. j. a combination of tag-free gesture recognition and mobile AR, when programming industrial robots. Caruso et al. [25] proposed an interactive AR system that allows the user to freely interact with virtual objects integrated in the real environment, thus avoiding using large and heavy equipment. The adoption of AR in the vision of Industry 4.0 [46] was proposed by Yew et al. [47] to improve the perception of information about different types of worker interactions in the environment. Liu et al. [48] and Rohidatun et al. [49] instead proposed AR solutions for welder training and assembly/disassembly training. The last two research topics in technical articles were calibration and ergonomics. The calibration of AR devices was dealt with by Canessa et al. [50] for the case of a color camera, Liu et al. [51] for a guidance system for AR, Kellner et al. [41] for HMD and Eck et al. [42], Itoh et al. [52] and Moser et al. [43] for OST-HDM. Ergonomic problems were instead investigated by Schega et al. [53], who assessed how basic visual functions are affected in different HMDs and how this relates to their effectiveness in AR, and Tuma et al. [54] who used AR to assess the ergonomic status of the workplace.

2.3 Application Articles

About 90 application articles were studied to find the most common keywords that showed the most popular AR application areas (see Fig. 2). The research showed that AR applications in industry are most focused on maintenance (21.2%), design (19.02%), assembly (11.9%) and training (7.8%). VR (13.4%), 3D models (9.3%), remote support (6.7%), mobile applications (5.5%) and holographic technologies (5.5%) are the most relevant types of applications developed.

From Fig. 2, it can be seen that there are 9 well-established research topics for the application articles related to AR applications in assembly, maintenance, design/prototyping and training. Assembly has emerged as a well-established research topic for both application and technical papers. That is, many works have focused either on the development of AR hardware/software solutions for assembly or on the application of AR in guiding operators in assembly tasks. Application articles focused mainly on this last aspect [55–57]; the same approach can be easily extended to the disassembly process as done by Tegeltija et al. [59, 60]. Zhang et al. [61] integrated AR with radio frequency identification (RFID) technology to guide operators in the assembly process. Mourtzis et al. [62] presented a more advanced solution and proposed an automated approach for remote support of assembly workplaces, with operators using augmented reality technology. One of the most interesting applications of AR in assembly was presented by de Araujo et al. [63]. Their work identified the most feasible way to provide an augmented reality-based learning facility to support the development of skills among the deaf to prepare for computer assembly line jobs. Product design issues are sometimes linked to assembly issues, as both activities are critical to product development. Product design problems are sometimes integrated with assembly problems because both actions are crucial to product development [64].

AR applications that focus heavily on product design problems have been investigated by Januszka and Moczulski [65], Huang et al. [66], Luh et al. [67], Yang et al. [68],

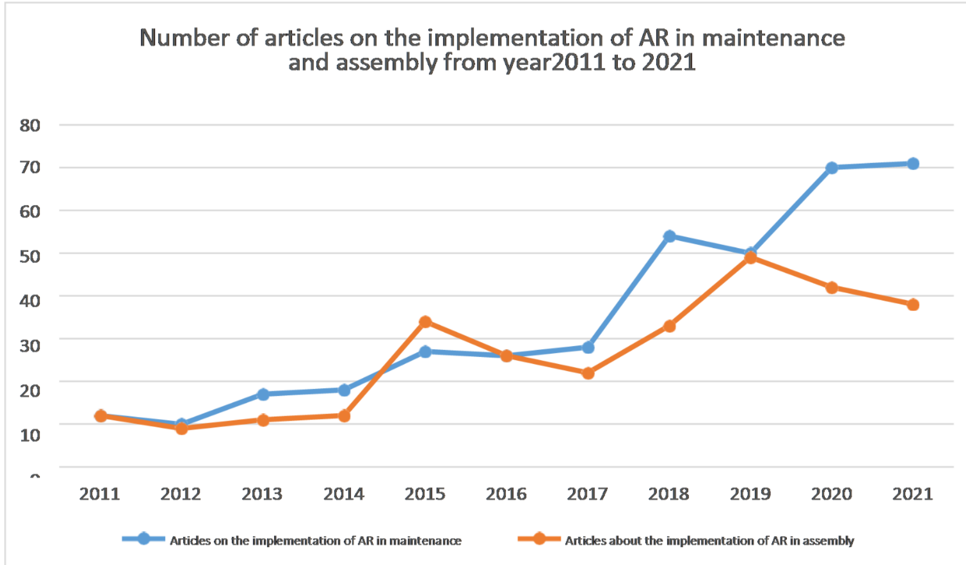

Fig. 3 Number of articles on the implementation of AR in maintenance and assembly from 2011 to 2021

Baron et al. [69]. Maintenance is another well-established area of use for AR technology; the purpose of implementing AR in this area can be either to train employees on maintenance tasks [70–72] or to increase efficiency and accuracy by supporting and guiding employees and avoiding errors or safety problems [73–79]. AR is particularly useful when maintenance activities should be performed in a hazardous environment [80–83] or when the machine/equipment is complex [84, 85]. Some articles have been devoted to imple-menting AR to improve the accuracy and efficiency of the order picking process [86, 87]. Other application articles include AR applications for CAD, quality control and tracking. In the field of CAD, Januszka and Moczulski [65] adopted AR to help designers develop machine systems; Fiorentino et al. [88] instead proposed a design inspection workspace that acquires user motion using a combination of video and depth cameras and visualizes CAD models using monitored AR. Franceschini et al. [89] proposed using AR for quality control. New research topics include the use of AR for safety, learning, training, ergonomics, remote applications (especially remote maintenance and support), and layout planning. The use of AR for occupational safety is a very current topic. The rationale for adopting AR for security is that this technology can reduce some risk factors for occupational accidents, namely insufficient training or work experience and the monotony of performed tasks. In terms of learning, AR has been adopted in e-learning [90] and mobile learning environments [91]. Vignais et al. [92] proposed an AR-based tool to assess the ergonomic conditions of workers with particular attention to potential risks for musculoskeletal disorders. Matteucci et al. [93] dealt with ergonomic problems related to an AR-based assembly process. Remote maintenance/support applications using AR were proposed by Adcock and Gunn [94], Gurevich et al. [95], Mourtzis et al. [96] and Neges et al. [97]. SAR (En-glish spatial augmented reality), i.e. spatial augmented reality, and MAR (English mobile augmented reality), i.e. mobile augmented reality, are among the new technical solutions. SAR increases real-world objects and scenes without using displays such as monitors, HMDs, or handheld devices; instead, it uses digital projectors to display visual infor-mation on physical objects. MAR systems use one or more tracking technologies: digital cameras and/or other optical sensors, accelerometers, GPS, gyroscopes, compasses, RFID, and wireless sensors [98]. SAR has been used to increase the accuracy of car manufacturing processes [99].

2.4 Conceptual Articles

Conceptual articles include mainly empirical/statistical studies and positional studies, with some exceptions, such as the study by Elia et al. [100]. They proposed a decision support system to help production managers in choosing the most effective AR solution to be used in specific production processes. Position papers usually describe the potential of using AR in various fields, including virtual manufacturing [101], "M-learning" [102] and lean manufacturing [103]. A study by Langley et al. [104] also focused on the effectiveness of AR systems for user training. Regarding statistical studies, Radkowski et al. [105] evaluated different visual properties for developing AR-based assembly instructions with increasing difficulty levels. Their hypothesis for this study was that the complexity of the optical element should correspond to the difficulty of the assembly task; therefore, the final goal was to match different types of visual properties of AR systems to varying levels of complexity of assembly tasks. Again in the field of assembly, Hou and Wang

[106] evaluated the effect of "gender" on the post-training performance of novice assemblers by analyzing the learning curves of test users with two methods of assembly (e.g., AR versus 3D manuals). Similar analyzes were performed by Fiorentino et al. [107] and Re et al. [108], who empirically evaluated the effectiveness of maintenance operations using interactive AR instructions compared to paper instructions in terms of execution time and the error rate of test users. Rehman and Cao [109] also performed a technical comparison of two solutions for AR, i.e. j. of a wearable device on the head and a hand-held device (smartphone), compared to paper solutions. Aromaa and Väänänen [110] compared an AR prototype and a VR prototype in terms of their suitability to support human factors/ergonomics evaluation during the design/prototyping phase. Some statistical studies have focused on the adoption of AR technology. Nakanishi and Sato [111] analyzed the behavioural, physiological and psychological effects of digital manuals presented with retinal imaging (RID) on workers in the manufacturing industry. Rapaccini et al. [112] provided the results of field research on the acceptance of AR by users to support the provision of services (e.g. maintenance activities) on installed products and Olsson et al. [113] conducted a similar study and evaluated user acceptance of five different mobile AR scenarios as well as explained the potential and risks of mobile AR in general.

3 Research and Research Task

3.1 Areas of Augmented Reality (AR) Implementations in the Industry

The literature review results confirm that assembly and maintenance are the most popular AR application areas, as they are mentioned (either as primary or secondary AR application areas) in approximately 18% of the articles. In addition, all types of the paper focused on these areas, although the application and technical papers predominate. The next most widespread areas of AR adoption are training/learning, product design, security, remote assistance and robotics. It is worth noting that some application areas are often considered together: this is for example the case of assembly and training, maintenance and remote assistance, maintenance and training, safety and ergonomics, and assembly and product design. The literature review results confirm that assembly and maintenance are the most popular AR application areas, as they are mentioned (either as primary or secondary AR application areas) in approximately 15% of the articles.

Furthermore, all paper types focused on these areas, although the application and technical papers predominated. The other most widespread areas of AR application are training/learning, product design/prototyping, security, remote support and robotics. It is worth noting that some application areas are often considered together: for example, the case of assembly and training, maintenance and remote support, maintenance and training, safety and ergonomics, and assembly and product design. A look at the development of application areas over time shows that interest in the adoption of AR in the field of assembly and maintenance (in the industry) has grown over time: from 2011 to 2016, 110 articles indexed by the Web of Science were published that contained the application of AR in maintenance and from 2017 to 2021, 273 articles were published on this topic; from 2011 to 2016, 104 Web of Science indexed articles were published that included the application of AR in montage, and from 2017 to 2021, 184 articles were published on the topic.

It means that these areas of AR application, although quite explored, are still attracting new research. Similar considerations can be made for implementing AR for training/learning purposes. Security, telerobotics/robotics, and remote support are AR application areas that have emerged recently and are now being explored with good continuity. The analysis and review of the relevant literature showed that in most cases, the implementation of AR was carried out in laboratory conditions, which prevents the possibility of identifying a specific industry. In most cases, this is the case with technical articles. However, any AR solution is ultimately expected to leave the laboratory and be used in a real industrial context; in this regard, laboratory studies usually represent a proof of concept for the usability of AR and should be considered as the first step for developing a solution. Among the studies carried out in the industrial sector, the most popular contexts in which AR has been implemented are engineering production, machine tools and equipment, control systems and the automotive industry. Other sectors that are less frequent in the studied studies are the aerospace, chemical, food, footwear and electronic industries, warehouse process management, and nuclear power plant. The cost-effectiveness, benefits and scalability of AR solutions in these contexts still need to be demonstrated. Most implementations of AR in assembly have been done in a laboratory setting or focused on the machine tool industry. AR studies in the manufacturing industry have instead primarily focused on maintenance or product design issues. Interestingly, AR studies focused on ergonomics problems were carried out in laboratory conditions, and there is still a lack of examples of practical applications in industry.

3.2 Technological Development of Augmented Reality

The technological solutions adopted to implement AR systems were examined as part of the literature review. Augmented Reality (AR) describes a combination of technologies that allow the real-time mixing of computer-generated content with live video displays. AR is based on techniques developed in virtual reality (VR) and interacts not only with the virtual world but is to some extent connected with the real one. The general principle of operation of augmented reality in all cases is as follows: the camera of the AR device (it can be mobile devices, computers, head-mounted displays, glasses, lenses, etc.) captures an image of a real object; the device software identifies the received image, combines the real picture with its complement and displays the resulting image on the visualization device. Each AR system consists of 3 components - hardware, software and application.

Hardware refers to the device through which virtual images are projected. These include mobile devices, smart glasses, head-mounted displays and web-based AR. The device must have sensors and processors that can satisfy the high requirements of AR. The key hardware components are the processor, graphics processing unit, sensors (depth sensor, gyroscope, proximity sensor, action-lerometer, and light sensor).

Software – the second part of the AR system. ARKit (Apple) and ARCore (Android) are some software examples and contain three basic technologies for AR. These 3 core technologies are environmental understanding, motion tracking, and light estimation.

The app is the last part of the AR system. The software allows running AR applications on the device but does not have AR functions. AR properties, such as 3D objects, come from special applications.

Most of the reviewed articles describe all components of AR solutions; however, some articles describe more than one AR application (and thus the hardware components are more numerous), while other articles (especially technical articles, overview articles, or conceptual articles) do not always focus on describing the entire AR architecture. As a result, the number of solutions described does not reflect the number of published studies.

"Camera" or its variant "camera connected to the monitor" is the most frequently used solution for capturing the outdoor environment scene. The monitor will display the scene to the user with relevant additional information. Another technological solution often used for visualization purposes is the HMD. Compared to the first solution, the HMD is easier to transport and does not require the installation of cameras or monitors in the production area. HMD solutions have increased slightly over time: as of 2011, more than six papers use this solution per year. However, some authors have criticized the use of HMDs, especially for remote support [114]; in fact, using an HMD could force the worker to limit head movements to stabilize the view for the remote assistant.

According to studies published since 2011, most technological visualization solutions use tablets, smartphones or other mobile devices, such as ultra-mobile computers. In this case, the environment is captured by the device's camera and immediately visualized by overlaying digital information on the display. Compared to HMD solutions, the use of tablets or smartphones is more socially accepted, and their advantage is even easier portability. However, mobile devices are held in hand during service, which can hinder the operator when he has to perform manual tasks (e.g. assembly or maintenance). For this reason, "bare-hand" solutions have been designed since 2011, with bare hands. Those solutions aim to develop intuitive manual interaction with virtual objects. In some articles, unconventional AR systems have been developed. Jimeno-Morenilla et al. [115] provided an example of using an unconventional system, i.e. j. infrared emitter connected to a pair of active glasses. Similarly, Liu et al. [116] described the technical problem of AR systems equipped with holographic displays. Li et al. [117] proposed a method to realize the three-dimensional transparent augmented reality in Fourier holographic displays.

Linking the technology solutions to the primary application area of AR use showed that cameras, HMDs and tablets/smartphones were adopted in almost all AR application areas. HMDs and mobile devices slightly predominate in areas where user guidance should be provided, i.e. j. assembly and maintenance. This is consistent with the fact that HMD instructions are more efficient than paper instructions and that using mobile devices reduces the risk of errors in assembly operations. An example is the application of AR in the assembly workplace of a drone factory at the Swedish National Test Laboratory [119]. The drone factory relied mainly on conventional operator support, such as paper instructions and animated visual illustrations on the monitor. This study focused on three aspects related to the new possibilities associated with the AR system. First, different ways of presenting instructions based on a structure and active diagram were included. Tablets and Microsoft HoloLens were also used in the study. Finally, two controls were included to demonstrate the instructions triggered by touch screen buttons and voice commands. Therefore, an

AR mounting support system with these features was developed and tested. The results showed that assembly operations with instructions based on the functional diagram were completed faster and with higher accuracy than the same operations were completed according to the structure diagram-based approach. Operators who used tablets performed better on average than those who used HoloLens.

Tracking systems for AR can be divided into two main categories: marker-based AR and marker-free AR. The analysis of the selected works shows that systems based on brands are the most frequently accepted solutions, as mentioned in most of the reviewed works. Marker-based AR has been implemented in both older and newer studios, with an increase in use in recent years. In these systems, tags are used to allow the AR system to recognize the object on which the title is placed and provide related information when needed. The analyzed studies used barcodes/QR codes, exit tags, optical tags, physical tags or RFID tags for this purpose. ARs without tags are mentioned in fewer articles. When tagless systems are used, several different solutions can be used to track objects. For example, Abhishek et al. [118] introduced a label-free AR virtual laboratory, Fiorentino et al. [78], and Neges et al. [120] used natural markers, i.e. Brands already available locally and that, thanks to their specific shape or colour, have great potential for optical tracking.

3.3 Results of Augmented Reality Implementation

Almost every study conducted either a technical test or a user study. In most articles, a user study was conducted to evaluate the benefits that arise when AR systems (instead of traditional methods) are used to assist the user in performing a task; in addition, nearly 20 articles propose a technical test of the developed application to show how it works. Most of the technical documents carried out a technical test aimed at assessing the functioning of the developed technological solutions; on the contrary, user studies are more limited in number. User tests were also performed in 12 conceptual documents and one review article. In terms of outcomes, many studies apparently measured more than one outcome produced by AR implementation. The distribution of the observed results depending on the type of test performed (either user studies or technical tests), and the classification of articles shows that specialised tests are mainly intended to evaluate the effectiveness of technical solutions. Technical studies that tested the effectiveness of the developed solution contribute to this result. The articles in which user studies were carried out focus primarily on evaluating the saving of time needed to perform a specific task. Other frequently measured results in user studies are aga-in the performance of the technical solution in terms of its efficiency and ease of use and the possibility of reducing errors associated with the performed task.

By linking the results observed through user studies or engineering tests to the primary area of use for AR (if specified), it was determined that assembly and maintenance could benefit the most from performing tasks faster. Better training results are typical of an AR application targeting learning/training problems. Testing the effectiveness of a developed solution is an important aspect of many AR application areas, including assembly, maintenance, product design/prototyping, and telerobotics/robotics. Among the studies that conducted a thorough assessment of the benefits generated by AR applications, De Crescenzio et al. [80] presented a prototype based on an AR system to assist operators in performing maintenance tasks on aircraft. Their proposed system was tested with 10 operators who demonstrated better performance and satisfaction when using the prototype. Operators were asked to evaluate the system; workload, performance and satisfaction with use were rated positively. Webel et al.

[70] presented an AR system that can be used to train and guide technicians in complex assembly and maintenance tasks. The application was tested at Sidel. The results obtained with this application showed that AR positively affected the performance of maintenance tasks: technicians equipped with the application needed 14% less time to complete the assigned task. The average number of unsolved errors reached 0.30 for qualified operators and 1.30 for unequipped operators. The only drawback was that after adopting the AR application, employees' training time increased by 20%. The subjects involved in the test were of the same age and had equivalent work experience. AR also shows potential for operations requiring remote support.

For example, Gurevich et al. [95] developed a remote collaboration system called "tele-advisor" that allows an expert to remotely guide a local user who needs assistance in performing physical tasks around real-world objects. The system was tested on 24 users, of which four worked as remote assistants and 20 as local users. The participants perceived the telecounsellor prototype as having good potential to facilitate and speed up daily tasks; moreover, most of the users, acting as helpers and workers, could easily understand how to use the system.

4 Conclusion and Discusion

The literature review was conducted on the basis of articles indexed by the Web of Science database, which were published between 2011 and 2021 and was focused on the implementation of AR in the industry. These articles were divided into overview, conceptual, technical and application. Review and conceptual pieces, which are fewer in number, were examined individually; application and technical articles were instead analyzed by identifying the most used keywords, which led to the identification of the main research topics and their level of dissemination in the scientific community. Further analyses were then conducted focusing on AR application areas, technology development, and the main results of AR application.

4.1 The Current Position of Ar in the Manufacturing Industry

The following considerations result from the comprehensive set of analyzes performed. First, interest in using AR technology in industrial operations has been growing over time, as highlighted by the growing number of recent works focusing on using AR in industry. Second, it can be stated that AR shows great application potential in many industrial areas, especially in the field of maintenance and assembly. In addition, it has also been shown to be useful in various (less explored) areas such as remote support, training/learning, facility management or inspection, and product design/prototyping.

Most of the published work has evaluated the benefits that AR systems can generate in industry compared to traditional techniques, either through user studies or technical tests. Whenever a quantitative analysis is performed, AR applications show interesting benefits in terms of reducing the time required to complete a given task and the number of employee errors; a positive impression of the AR solution (whether in terms of efficiency, intuitiveness or ease of use) is also often observed.

4.2 The Most Reviewed/Promising/Popular AR Apps

Some specific application areas of AR were explored in detail in both application and technical articles that focused on the implementation of AR in assembly, maintenance, product design and training/learning. Other interesting application areas are safety, ergonomics or remote support/remote collaboration, which are now being investigated with better continuity. However, the number of studies found is still limited and suggests that the potential of AR in these contexts has not yet been fully explored. Other aspects often discussed in the literature are technical and technological issues related to the development and implementation of AR systems intended for an industrial context.

Many articles (especially technical and application papers) describe in detail tracking technologies, visualization technologies and the rationale for choosing such technological solutions. In most of the studied studies, specialised visualization solutions use mobile devices (such as tablets, smartphones or ultra-mobile computers) or HMDs. Additionally, tablets or HMDs are easier to carry, and employees usually have no problems using them, making these devices more likely to be implemented in these contexts. However, mobile devices are hand-held during use, which can hinder the operator when performing manual tasks (e.g. assembly or maintenance tasks, often the focus of AR applications). However, HMDs have been criticized because their use can cause ergonomic problems. Therefore, other technologies (for example, "bare-hand" solutions) have appeared to develop natural and intuitive manual interaction with virtual objects. Overall, from a practical point of view, these results suggest that the choice of implemented device ultimately depends on the field of application of the AR system. Regarding tracking technology, tag-based ARs are usually preferred, probably due to better accuracy than tag-free ARs and ease of implementation.

4.3 "Research Gap" and Future Direction of Research

Many technical studies were conducted only in laboratory conditions without implementing the AR system in a real context; as a result, there is a lack of real implementations for AR solutions focused on specific areas, e.g. ergonomics. As AR solutions are ultimately expected to be used in real industrial contexts, further research activities should be conducted to develop scalable AR solutions in less explored areas.

Based on the findings from this review, it is possible to direct future research activities to research areas that were only minimally addressed in the research works. First, there is a need to further explore the industrial areas in which AR systems could be successfully implemented. For this purpose, it is necessary to focus mainly on training/learning, ergonomics/safety, remote monitoring, human-robot cooperation and production management. Secondly, although the benefits of AR adoption have been evaluated in many studies, the design and implementation of an AR system also involve high costs. Therefore, an economic assessment of the prices and savings generated by the performance of AR is needed. To this end, the development of an AR solution should be considered an investment, which means that after performance, its use will continue for several years; investment evaluation is probably the most appropriate approach to assess whether and how quickly the invested funds are invested will be returned. It is clear that carrying out such an evaluation and generalizing the results requires many AR applications in the coming years.

A third aspect that needs to be explored in future research is assessing the manufacturing industry's interest in and knowledge of using AR solutions to improve its process performance. This analysis should possibly focus on those countries in which a very limited number of applications of AR solutions have been found. Investigating the interest in AR solutions and the level of knowledge about these solutions can be carried out, for example, using empirical analyses, such as questionnaire surveys aimed at manufacturing companies operating in these countries. Whenever there is interest in the application of AR, the next thing to investigate is the specific application areas (e.g., logistics, production and facility management, quality and safety, or maintenance) that are considered promising for AR implementation. This can again be done using empirical research. In general, research focuses on implementing AR in assembly, maintenance, human-robot collaboration or remote support, as these are the most promising application domains, while the latter two are underexplored. Our further research focuses on implementing AR in one of these areas, taking into account the ergonomic factor and the profitability of the investment, which can bring new scientific knowledge.

4.4 Key Methodological Approach and Procedure

After analyzing how AR has been implemented in various industrial areas, it is possible to outline a certain procedure for its implementation:

1. Identification of problems.
2. Analysis of needs.
3. Designing the system.
4. Development and documentation.
5. System testing.

1) Identification of problems - This is the first and most important stage in which specific production problems must be identified. To accurately define the scope of the problem, knowledge and experience in related production areas is required. Interviews and background checks conducted in manufacturing companies effectively identified potential problems.

2) Need analysis - After identifying the problem, the next phase specifies the system requirements. It includes the alignment between a technological solution and a specific issue.

3) Designing the system - In this phase, the information collected in the previous phases is used to achieve a logical design of the AR system, while the exact data entry procedure is defined. All cases encountered some difficulty at this stage due to the different data formats used in the existing systems. Data conversion has become a necessary step in all cases. This is time-consuming and potentially affects data quality.

4) Development and documentation - This phase refers to the actual work on the implementation of the AR system. Most AR implementations used the Unity3D open platform for integration and programming. The hardware was also selected based on the area of use.

5) System testing -Users must then test the developed system. It can take place when the entire system has been completed or when parts of the features have been designed. In most cases described in the reviewed articles, user tests or technical tests were used, and most AR applications were implemented in laboratories. To ensure the result of the developed system, it is necessary to perform such tests several times. However, it is also about the balance between the complexity of the project and the available resources.

Acknowledgements This work was supported by the projects VEGA 1/0268/22, KEGA 038TUKE-4/2022 granted by the Ministry of Education, Science, Research and Sport of the Slovak Republic.

Funding This paper is part of a project that has received funding from the Ministry of Education, Science, Research and Sport of the Slovak Republic under grant agreement KEGA 038TUKE-4/2022.

Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Conflicts of Interest/Competing Interests Not applicable. Without conflicts of interest/competing interests.

References

1. Schuettel P (2017) The concise fintech compendium. School of Management Fribourg, Switzerland, Fribourg
2. Grubert J, Langlotz T, Zollmann S et al (2017) Towards pervasive Augmented Reality: Context- awareness in Augmented Reality. In: IEEE Transactions on Visualization and Computer Graphics, vol. 23, no. 6, pp. 1706–1724. https://doi.org/10.1109/TVCG.2016.2543720
3. Bottani E, Vignali G (2019) Augmented reality technology in the manufacturing industry: A review of the last decade, IISE Transactions, vol. 51, no. 3, pp. 284–310. https://doi.org/10.1080/24725854.2018.1493244
4. Georgel P (2011) Is there a reality in industrial augmented reality? In: Proceedings of the 10th IEEE International Symposium on Mixed and Augmented Reality, OCT 26–29, 2011, Basel, IEEE Press, pp. 201–210. https://doi.org/10.1109/ISMAR.2011.6092387
5. Igarashi T, Inami M (2015) Exploration of alternative interaction techniques for robotic systems. In: IEEE Computer Graphics and Applications, vol. 35, no. 3, pp. 33–41. https://doi.org/10.1109/MCG.2015.24
6. De Pace F, Manuri F, Sanna A, Fornaro C (2020) A systematic review of augmented reality interfaces for collaborative industrial robots. Comput Ind Eng 149. Article Number 106806https://doi.org/10.1016/j.cie.2020.106806
7. Leu MC, ElMaraghy HA, Nee AYC, Ong SK, Lanzetta M, Putz M, Zhu WJ, Bernard A (2013) CAD model based virtual assembly simulation, planning and training. In: CIRP

Annals-Manufacturing Technology, vol. 62, no. 2, pp. 799–822. https://doi.org/10.1016/j.cirp.2013.05.005
8. Wang X, Ong SK, Nee AYC (2016) A comprehensive survey of augmented reality assembly research. In: Advances in Manufacturing, vol. 4, no. 1, pp. 1–22. https://doi.org/10.1007/s40436-015-0131-4
9. Oliveira ACM, Araujo RB, Jardine AKS (2013) A human centered view on E-maintenance. Chem Eng Trans 33:385–390. https://doi.org/10.3303/CET1333065
10. Lamberti F, Manuri F, Sanna A, Paravati G, Pezzolla P, Montuschi P (2014) Challenges, opportunities, and future trends of emerging techniques for augmented reality-based maintenance. IEEE Trans Emerg Top Comput 2(4):411–421. https://doi.org/10.1109/TETC.2014.2368833
11. Palmarini R, Erkoyuncu JA, Roy R, Torabmostaedi H (2018) A systematic review of augmented reality applications in maintenance. In: Robotics and Computer-Integrated Manufacturing, vol. 49, pp. 215–228. https://doi.org/10.1016/j.rcim.2017.06.002
12. Nee AYC, Ong SK, Chryssolouris G, Mourtzis D (2012) Augmented reality applications in design and manufacturing. CIRP Annals - Manufacturing Technology, vol. 61, no. 2, pp. 657–679. https://doi.org/10.1016/j.cirp.2012.05.010
13. Yin YH, Nee AYC, Ong SK, Zhu JY, Gu PH, Chen LEJ (2015) Automating design with intelligent human-machine integration. In: CIRP Annals - Manufacturing Technology, vol. 64, no. 2, pp. 655–677. https://doi.org/10.1016/j.cirp.2015.05.008
14. Vanderroost M, Ragaert P, Verwaeren J, de Meulenaer B, de Baets B, Devlieghere F (2017) The digitization of a food package's life cycle: Existing and emerging computer systems in the logistics and post-logistics phase. In: Computers in Industry, vol. 87, pp. 15–30. https://doi.org/10.1016/j.compind.2017.01.004
15. Wang ZB, Ng LX, Ong SK, Nee AYC (2013) Assembly planning and evaluation in an augmented reality environment. Int J Prod Res 51:23–24. https://doi.org/10.1080/00207543.2013.837986
16. Wang ZB, Ong SK, Nee AYC (2013) Augmented reality aided interactive manual assembly design. In: International Journal of Advanced Manufacturing Technology, vol. 69, no. 5–8, pp. 1311–1321. https://doi.org/10.1007/s00170-013-5091-x
17. Nee AYC, Ong SK, Chryssolouris G, Mourtzis D (2012) Augmented reality applications in design and manufacturing. In: Cirp Annals-Manufacturing Technology, vol. 61, no. 2, pp. 657–679. https://doi.org/10.1016/j.cirp.2012.05.010
18. Arbelaez JC, Vigano R, Osorio-Gomez G (2019) Haptic Augmented Reality (HapticAR) for assembly guidance. In: International Journal of Interactive Design and Manufacturing - IJIDEM, vol. 13, no. 2, pp. 673–687. https://doi.org/10.1007/s12008-019-00532-3
19. Dhiman H, Buttner S, Rocker C, Reisch R (2020) Handling Work Complexity with AR/Deep Learning. In: PROCEEDINGS OF THE 31ST AUSTRALIAN CONFERENCE ON HUMAN-COMPUTER-INTERACTION (OZCHI'19), December 2–5, 2019, New York, USA, pp. 518–522. https://doi.org/10.1145/3369457.3370919
20. Faccio M, Ferrari E, Galizia FG, Gamberi M, Pilati F (2019) Real-time assistance to manual assembly through depth camera and visual feedback. In: Proceeding of the 52nd CIRP Conference on Manufacturing Systems (CMS), JUN 12–14, 2019, Ljubljana, Slovenia, vol. 81, pp. 1254–1259. https://doi.org/10.1016/j.procir.2019.03.303
21. Radkowski R (2016) Object tracking with a range camera for augmented reality assembly assistance. J Comput Inf Sci Eng 16(1):1–8. https://doi.org/10.1115/1.4031981
22. Chen XW, Jin X, Wang K (2014) Lighting virtual objects in a single image via coarse scene understanding. Sci China Inform Sci 57 9, Article Number 092105. https://doi.org/10.1007/s11432-013-4936-0
23. Jimeno-Morenilla A, Sanchez-Romero JL, Salas-Perez F (2013) Augmented and virtual reality techniques for footwear. In: Computers in Industry, vol. 64, no. 9, pp. 1371–1382. https://doi.org/10.1016/j.compind.2013.06.008
24. Mourtzis D, Papakostas N, Mavrikios D, Makris S, Alexopoulos K (2015) The role of simulation in digital manufacturing: applications and outlook. Int J Comput Integr Manuf 28(1):3–24. https://doi.org/10.1080/0951192X.2013.800234
25. Caruso G, Carulli M, Bordegoni M (2015) Augmented reality system for the visualization and interaction with 3D digital models in a wide environment. In: Computer-Aided Design and Applications, vol. 12, no. 1, 86–95. https://doi.org/10.1080/16864360.2014.949579
26. Ajanki A, Billinghurst M, Gamper H et al (2011) An augmented reality interface to contextual information. In: Virtual Reality, vol. 15, no. 2–3, pp. 161–173. https://doi.org/10.1007/s10055-010-0183-5
27. Benbelkacem S, Belhocine M, Bellarbi A et al (2013) Augmented reality for photovoltaic pumping systems maintenance tasks. In: Renewable Energy, vol. 55, pp. 428–437. https://doi.org/10.1016/j.renene.2012.12.043
28. Ludwig T, Doll M, Kotthaus C (2019) The Printer is Telling Me about Itself: Supporting the Appropriation of Hardware by Using Projection Mapping. In: PROCEEDINGS OF THE 2019 ACM DESIGNING INTERACTIVE SYSTEMS CONFERENCE (DIS 2019), June 24–28, 2019, San Diego, USA, pp. 331–344. https://doi.org/10.1145/3322276.3322342
29. Mourtzis D, Doukas M, Vandera C (2014) Mobile apps for product customisation and design of manufacturing networks. In: Manufacturing Letters, vol. 2, no. 1, pp. 30–34. https://doi.org/10.1016/j.mfglet.2014.01.002
30. Verbelen T, Simoens P, de Turck F et al Adaptive deployment and configuration for mobile augmented reality in the cloudlet. In: Journal of Network and Computer Applications, vol. 41, no. 1, pp. 206–216. https://doi.org/10.1016/j.jnca.2013.12.002
31. Han P, Zhao G (2015) CAD-based 3D objects recognition in monocular images for mobile augmented reality. Computers and Graphics 50:36–46. https://doi.org/10.1016/j.cag.2015.05.021
32. Kim M, Lee JY (2016) Touch and hand gesture-based interactions for directly manipulating 3D virtual objects in mobile augmented reality. In: Multimedia Tools and Applications, vol. 75, no. 16, pp.16529– 16550. https://doi.org/10.1007/s11042-016-3355-9
33. Shatz N, Bortz J, Squire M (2018) Demonstration of Augmented-Reality Optical Narrowcasting. In: Proceeding of the 15TH IEEE ANNUAL CONSUMER COMMUNICATIONS & NETWORKING CONFERENCE (CCNC), JAN 12–15, 2018, Las Vegas, NV, USA
34. Chen HX, Dai YT, Meng H, Chen YL, Li T (2018) Understanding the Characteristics of Mobile Augmented Reality Applications. In: Proceedings of the IEEE International Symposium On Performance Analysis Of Systems And Software (ISPASS), Belfast, North Ireland, APR 02–04, pp.128–138, 2018. https://doi.org/10.1109/ISPASS.2018.00026
35. Koch C, Neges M, Konig M, Abramovici M (2004) Natural markers for augmented reality-based indoor navigation and facility maintenance. Autom Constr 48:18–30. https://doi.org/10.1016/j.autcon.2014.08.009
36. Vignali G, Bertolini M, Bottani E et al (2018) Design and testing of an augmented reality solution to enhance operator safety in the food industry. Int J Food Eng article number 20170122. https://doi.org/10.1515/ijfe-2017-0122
37. De Marchi L, Ceruti A, Marzani A, Liverani A (2013) Augmented reality to support on-field post- impact maintenance operations on thin structures. J Sens Article numeber 619570. https://doi.org/10.1155/2013/619570

38. Koch C, Neges M, Konig M, Abramovici M (2014) Natural markers for augmented reality-based indoor navigation and facility maintenance. In: Automation in Construction, vol. 48, pp. 18–30. https://doi.org/10.1016/j.autcon.2014.08.009
39. Stylianidis E, Valari E, Pagani A, Carrillo I et al (2020) Augmented Reality Geovisualisation for Underground Utilities. In: PFG-JOURNAL OF PHOTOGRAMMETRY REMOTE SENSING AND GEOINFORMATION SCIENCE, vol. 88, no. 2, pp. 173–185. https://doi.org/10.1007/s41064-020-00108-x
40. Weng D, Cheng D, Wang Y, Liu Y (2012) Display systems and registration methods for augmented reality applications. In: Optik, vol. 123, no. 9, pp. 769–774. https://doi.org/10.1016/j.ijleo.2011.05.033
41. Kellner F, Bolte B, Bruder G et al (2012) Geometric calibration of head-mounted displays and its effects on distance estimation. IEEE Trans Vis Comput Graph 18(4):589–596. https://doi.org/10.1109/TVCG.2012.45
42. Eck U, Pankratz F, Sandor C et al (2015) Precise haptic device co-location for visuo-haptic augmented reality. IEEE Trans Vis Comput Graph 21(12):1427–1441. https://doi.org/10.1109/TVCG.2015.2480087
43. Moser K, Itoh Y, Oshima K et al (2015) Subjective evaluation of a semi-automatic optical see-through head-mounted display calibration technique. IEEE Trans Vis Comput Graph 21(4):491–500. https://doi.org/10.1109/TVCG.2015.2391856
44. Orlosky J, Toyama T, Kiyokawa K et al (2015) ModulAR: Eye-controlled vision augmentations for head mounted displays. IEEE Trans Vis Comput Graph 21(11):1259–1268. https://doi.org/10.1109/TVCG.2015.2459852
45. Lambrecht J, Kleinsorge M, Rosenstrauch M (2013) Spatial programming for industrial robots through task demonstration. Int J Adv Rob Syst 10:254. Article numberhttps://doi.org/10.5772/55640
46. Drath R, Horch A (2014) Industrie 4.0: hit or hype. IEEE Ind Electron Mag 8(2):56–58. https://doi.org/10.1109/MIE.2014.2312079
47. Yew AWW, Ong SK, Nee AYC (2016) Towards a griddable distributed manufacturing system with augmented reality interfaces. In: Robotics and Computer-Integrated Manufacturing, vol. 39, pp. 43– 55. https://doi.org/10.1016/j.rcim.2015.12.002
48. Liu Y, Li S, Wang J (2015) Assembly auxiliary system for narrow cabins of spacecraft. Chin J Mech Eng 28(5):1080–1088. https://doi.org/10.3901/CJME.2015.0416.044
49. Rohidatun MW, Faieza AA, Rosnah MY et al (2016) Development of virtual reality (VR) system with haptic controller and augmented reality (AR) system to enhance learning and training experience. Int J Appl Eng Res 11(16):8806–8809
50. Canessa A, Chessa M, Gibaldi A et al (2014) Calibrated depth and color cameras for accurate 3D interaction in a stereoscopic augmented reality environment. In: Journal of Visual Communication and Image Representation, vol. 25, no. 1, pp. 227–237. https://doi.org/10.1016/j.jvcir.2013.02.011
51. Liu M, Yang S, Wang Z et al (2016) Generic precise augmented reality guiding system and its calibration method based on 3D virtual model. In: Optics Express, vol. 24, no. 11, pp. 12026–12042. https://doi.org/10.1364/OE.24.012026
52. Itoh Y, Dzitsiuk M, Amano T et al (2015) Semi-parametric color reproduction method for optical see- through head-mounted displays. IEEE Trans Vis Comput Graph 21(11):1269–1278. https://doi.org/10.1109/TVCG.2015.2459892
53. Schega L, Hamacher D, Erfuth S et al (2014) Differential effects of head-mounted displays on visual performance. Ergonomics 57(1):1–11. https://doi.org/10.1080/00140139.2013.853103
54. Tuma Z, Kotek L, Tuma J (2016) Application of augmented reality for verification of real workplace state. MM Sci J 1487–1490. https://doi.org/10.17973/MMSJ.2016_11_2016166
55. Ong SK, Wang ZB (2011) Augmented assembly technologies based on 3D bare-hand interaction. In: CIRP Annals - Manufacturing Technology, vol. 60, no. 1, pp. 1–4. https://doi.org/10.1016/j.cirp.2011.03.001
56. Gonzalez-Sanchez J, Conley Q, Chavez-Echeagaray ME et al (2012) Supporting the assembly process by leveraging augmented reality, cloud computing, and mobile devices. Int J Cyber Behav Psychol Learn 2(3):86–102. https://doi.org/10.4018/ijcbpl.2012070107
57. Liu Y, Li S, Wang J (2015) Assembly auxiliary system for narrow cabins of spacecraft. Chin J Mech Eng 28(5):1080–1088. https://doi.org/10.3901/CJME.2015.0416.044
58. Wang X, Ong SK, Nee AYC (2016) Multi-modal augmented reality assembly guidance based on bare- hand interface. In: Advanced Engineering Informatics, vol. 30, no. 3, pp. 406–421. https://doi.org/10.1016/j.aei.2016.05.004
59. Tegeltija SS, Lazarevic MM, Stankovski SV (2016) Heating circulation pump disassembly process improved with augmented reality. Therm Sci 20:S611–S622. https://doi.org/10.2298/TSCI150927043T
60. Koller J, Kemp D, Dopper F (2020) Supporting Disassembly in Remanufacturing with Augmented Reality. In: Proceedings of the IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD), NOV 24–27, Marrakech, MOROCCO. https://doi.org/10.1109/ICTMOD49425.2020.9380599
61. Zhang J, Ong SK, Nee AYC (2011) RFID-assisted assembly guidance system in an augmented reality environment. Int J Prod Res 49:3919–3938. https://doi.org/10.1080/00207543.2010.492802
62. Mourtzis D, Zogopoulos V, Xanthi F (2019) Augmented reality application to support the assembly of highly customized products and to adapt to production re-scheduling. Int J Adv Manuf Technol 105(9):3899–3910. https://doi.org/10.1007/s00170-019-03941-6
63. de Araujo TAC, Oliveira FCMB, Costa CL (2019) Creating job opportunities in computer assembly line for people with disabilities through augmented reality. In: Proceedings of the 49th IEEE Frontiers in Education Conference (FIE), OCT 16–19, Cincinnati, USA
64. Ng LX, Wang ZB, Ong SK et al (2013) Integrated product design and assembly planning in an augmented reality environment. In: Assembly Automation, vol. 33, no. 4, pp. 345–359. https://doi.org/10.1108/AA-10-2012-058
65. Januszka M, Moczulski W (2011) Augmented reality system for aiding engineering design process of machinery systems. J Syst Sci Syst Eng 20(3):294–309. https://doi.org/10.1007/s11518-011-5170-1
66. Huang SH, Yang YI, Chu CH (2012) Human-centric design personalization of 3D glasses frame in markerless augmented reality. In: Advanced Engineering Informatics, vol. 26, no. 1, pp. 35–45. https://doi.org/10.1016/j.aei.2011.07.008
67. Yang YI, Yang CK, Chu CH (2014) A virtual try-on system in augmented reality using RGB-D cameras for footwear personalization. J Manuf Syst 33(4):690–698. https://doi.org/10.1016/j.jmsy.2014.05.006
68. Kaščak J, Telišková M, Török J, Baron P, Zajac J, Husár J (2019) Implementation of Augmented Reality into the Training and Educational Process in Order to Support Spatial Perception in Technical Documentation, 2019 IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA), pp. 583–587. https://doi.org/10.1109/IEA.2019.8715120
69. De Crescenzio F, Fantini M, Persiani F et al (2011) Augmented reality for aircraft maintenance training and operations support. In: IEEE Computer Graphics and Applications, vol. 31, no. 1, pp. 96– 101. https://doi.org/10.1109/MCG.2011.4

70. Webel S, Bockholt U, Engelke T et al (2013) An augmented reality training platform for assembly and maintenance skills. In: Robotics and Autonomous Systems, vol. 61, no. 4, pp. 398–403. https://doi.org/10.1016/j.robot.2012.09.013
71. Westerfield G, Mitrovic A, Billinghurst M (2015) Intelligent augmented reality training for motherboard assembly. In: International Journal of Artificial Intelligence in Education, vol. 25, no. 1, 157–172. https://doi.org/10.1007/s40593-014-0032-x
72. Osborne M, Mavers S (2019) Integrating Augmented Reality in Training and Industrial Applications. In: Proceedings of the International Conference of Educational Innovation through Technology, OCT 27–31, Biloxi, USA, pp. 142–146. https://doi.org/10.1109/EITT.2019.00035
73. Henderson S, Feiner S (2011) Exploring the benefits of augmented reality documentation for maintenance and repair. In: IEEE Transactions on Visualization and Computer Graphics, vol. 17, no. 10, pp. 1355–1368. https://doi.org/10.1109/TVCG.2010.245
74. Lee S, Akin O (2011) Augmented reality-based computational fieldwork support for equipment operations and maintenance. In: Automation in Construction, vol. 20, no. 4, pp. 338–352. https://doi.org/10.1016/j.autcon.2010.11.004
75. Espındola DB, Fumagalli L, Garetti M et al (2013) A model-based approach for data integration to improve maintenance management by mixed reality. In: Computers in Industry, vol. 64, no. 4, pp. 376– 391. https://doi.org/10.1016/j.compind.2013.01.002
76. Ong SK, Zhu J (2013) A novel maintenance system for equipment serviceability improvement. In: CIRP Annals - Manufacturing Technology, vol. 62, no. 1, pp. 39–42. https://doi.org/10.1016/j.cirp.2013.03.091
77. Zhu J, Ong SK, Nee AYC (2014) A context-aware augmented reality system to assist the maintenance operators. In: International Journal on Interactive Design and Manufacturing, vol. 8, no. 4, pp. 293–304. https://doi.org/10.1007/s12008-013-0199-7
78. Kaščak J, Husár J, Knapčíková L, Trojanowska J, Ivanov V (2022) Conceptual use of augmented reality in the maintenance of Manufacting Facilities. In: Trojanowska J, Kujawińska A, Machado J, Pavlenko I (eds) Advances in Manufacturing III. MANUFACTURING 2022. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-99310-8_19
79. Young C, Rai R (2021) Automated Procedure Reconfiguration Framework for Augmented Reality- Guided Maintenance Applications. In: Journal of Computing and Information Science in Engineering, vol. 21, no. 6, Article Number 061011. https://doi.org/10.1115/1.4051054
80. De Crescenzio F, Fantini M, Persiani F et al (2011) Augmented reality for aircraft maintenance training and operations support. In: IEEE Computer Graphics and Applications, vol. 31, no. 1, pp. 96– 101. https://doi.org/10.1109/MCG.2011.4
81. Kostolani M, Murin J, Kozak S (2019) Intelligent predictive maintenance control using augmented reality. In: Proceedings of the 22nd International Conference on Process Control (PC19), JUN 11–14,Strbske Pleso, SLOVAKIA, pp. 131–135. https://doi.org/10.1109/PC.2019.8815042
82. Martınez H, Laukkanen S, Mattila J (2013) A new hybrid approach for augmented reality maintenance in scientific facilities. In: International Journal of Advanced Robotic Systems, vol. 10, Article number 321. https://doi.org/10.5772/56845
83. Nakai A, Suzuki K (2016) Instructional information system using AR technology for chemical plants. In:Chemical Eng Trans 53:199–204. https://doi.org/10.3303/CET1653034
84. Golanski P, Perz-Osowska M, Szczekala M (2014) A demonstration model of a mobile expert system with augmented reality user interface supporting M-28 aircraft maintenance. J Konbin 31(1):23–30. https://doi.org/10.2478/jok-2014-0020
85. Wojcicki T (2014) Supporting the diagnostics and the maintenance of technical devices with augmented reality. In: Diagnostyka, vol. 15, no. 1, pp.43–47
86. Hanson R, Falkenstrom W, Miettinen M (2017) Augmented reality as a means of conveying picking information in kit preparation for mixed-model assembly. Comput Ind Eng 113:570–575. https://doi.org/10.1016/j.cie.2017.09.048
87. Krajcovic M, Gabajova G, Micieta B (2014) Order picking using augmented reality. In: Komunikacie, vol. 16, no. 3A, pp. 106–111
88. Fiorentino M, Radkowski R, Stritzke C et al (2013) Design review of CAD assemblies using bimanual natural interface. In: International Journal on Interactive Design and Manufacturing, vol. 7, no. 4, pp. 249–260. https://doi.org/10.1007/s12008-012-0179-3
89. Franceschini F, Galetto M, Maisano D et al (2016) Towards the use of augmented reality techniques for assisted acceptance sampling. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 230, no. 10, pp. 1870–1884. https://doi.org/10.1177/0954405415624360
90. Sepasgozar SME (2020) Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering. In: APPLIED SCIENCES-BASEL, vol. 10, no. 13, Article Number 4678. https://doi.org/10.3390/app10134678
91. Jain P, Tucker C (2020) Mobile based real-time occlusion between real and digital objects in Augmented Reality. In: Proceedings of ASME International Design Engineering Technical Conferences/Computers and Information in Engineering Conference, AUG 18–21, Anaheim, California,Article Number UNSP V001T02A085
92. Vignais N, Miezal M, Bleser G et al (2013) Innovative system for real-time ergonomic feedback in industrial manufacturing. In: Applied Ergonomics, vol. 44, no. 4, pp. 566–574. https://doi.org/10.1016/j.apergo.2012.11.008
93. Matteucci M, Raponi D, Mengoni M et al (2017) Tangible augmented reality model to support manual assembly. In: Proceedings of ASME International Design Engineering Technical Conferences/Computers and Information in Engineering Conference (IDETC/CIE 2017), AUG 06–09, Cleveland, USA, Article Number UNSP V009T07A038
94. Adcock M, Gunn C (2015) Using projected light for mobile remote guidance. In: Computer Supported Cooperative Work: An International Journal, vol. 24, no. 6, pp. 591–611. https://doi.org/10.1007/s10606-015-9237-2
95. Gurevich P, Lanir J, Cohen B (2015) Design and implementation of TeleAdvisor: A projection-based augmented reality system for remote collaboration. In: Computer Supported Cooperative Work (CSCW): An International Journal, vol. 24, no. 6, pp. 527–562. https://doi.org/10.1007/s10606-015-9232-7
96. Mourtzis D, Vlachou A, Zogopoulos V (2017) Cloud-based augmented reality remote maintenance through shop-floor monitoring: A product-service system approach. In: Journal of Manufacturing Science and Engineering, Transactions of the ASME, vol. 139, no. 6, Article number 061011. https://doi.org/10.1115/1.4035721
97. Neges M, Koch C, Konig M et al (2017) Combining visual natural markers and IMU for improved AR based indoor navigation. Adv Eng Inform 31:18–31. https://doi.org/10.1016/j.aei.2015.10.005
98. Chatzopoulos D, Bermejo C, Huang Z et al (2017) Mobile augmented reality survey: from where we are to where we go. IEEE Access 5:6917–6950. https://doi.org/10.1109/ACCESS.2017.2698164
99. Doshi A, Smith RT, Thomas BH et al (2017) Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing. Int J Adv Manuf Technol 89:5–8. https://doi.org/10.1007/s00170-016-9164-5
100. Elia V, Gnoni MG, Lanzilotto A (2016) Evaluating the application of augmented reality devices in manufacturing from a process

point of view: An AHP based model. In: Expert Systems with Applications, vol. 63, pp. 187–197. https://doi.org/10.1016/j.eswa.2016.07.006
101. Duda J, Oleszek S (2020) Concept of PLM Application Integration with VR and AR Techniques. In: Advances in Production Management Systems: Towards Smart and Digital Manufacturing, PT II, vol. 592, pp 91–99. https://doi.org/10.1007/978-3-030-57997-5_11
102. Modlo YO, Semerikov SO, Bondarevskyi SL (2019) Methods of using mobile Internet devices in the formation of the general scientific component of bachelor in electromechanics competency in modeling of technical objects. In: Proceedings of the 2nd International Workshop on Augmented Reality in Education (AREdu), MAR 22, Kryvyi Rih, UKRAINE, vol. 2547, pp. 217–240
103. Huenerfauth AM (2014) Mobile technology applications for manufacturing, reduction of muda (waste) and the effect on manufacturing economy and efficiency. Int J Interact Mob Technol 8(4):20–23. https://doi.org/10.3991/ijim.v8i4.3797
104. Langley A, Lawson G, Hermawati S (2016) Establishing the usability of a virtual training system for assembly operations within the automotive industry. Hum Factors Ergon Manuf 26(6):667–679. https://doi.org/10.1002/hfm.20406
105. Radkowski R, Herrema J, Oliver J (2015) Augmented reality based manual assembly support with visual features for different degrees of difficulty. Int J Hum Comput Interact 31(5):337–349. https://doi.org/10.1080/10447318.2014.994194
106. Hou L, Wang X (2013) A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender. In: Automation in Construction, vol. 32, pp. 38–45. https://doi.org/10.1016/j.autcon.2012.12.007
107. Fiorentino M, Uva AE, Gattullo M et al (2014) Augmented reality on large screen for interactive maintenance instructions. In: Computers in Industry, vol. 65, no. 2, pp. 270–278. https://doi.org/10.1016/j.compind.2013.11.004
108. Re GM, Oliver J, Bordegoni M (2016) Impact of monitor-based augmented reality for on-site industrial manual operations. In: Cognition Technology & Work, vol. 18, no. 2, pp. 379–392. https://doi.org/10.1007/s10111-016-0365-3
109. Rehman U, Cao S (2017) Augmented-reality-based indoor navigation: A comparative analysis of handheld devices versus Google Glass. In: IEEE Transactions on Human-Machine Systems, vol. 47, no. 1, pp. 140–151. https://doi.org/10.1109/THMS.2016.2620106
110. Aromaa S, Väänänen K (2016) Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design. In: Applied Ergonomics, vol. 56, pp. 11–18. https://doi.org/10.1016/j.apergo.2016.02.015
111. Nakanishi M, Sato T (2015) Application of digital manuals with a retinal imaging display in manufacturing: behavioral, physiological, and psychological effects on workers. In: Human Factors and Ergonomics in Manufacturing & Service Industries, vol. 25, no. 2, pp. 228–238. https://doi.org/10.1002/hfm.20535
112. Rapaccini M, Porcelli I, Espındola DB et al (2014) Evaluating the use of mobile collaborative augmented reality within field service networks: the case of Oce Italia – Canon Group. In: Production and Manufacturing Research, vol. 2, no. 1, pp. 738–755. https://doi.org/10.1080/21693277.2014.943430
113. Olsson T, Kärkkäinen T, Lagerstam E et al (2012) User evaluation of mobile augmented reality scenarios. In: Journal of Ambient Intelligence and Smart Environments, vol. 4, no. 1, pp. 29–47. https://doi.org/10.3233/AIS-2011-0127
114. Gurevich P, Lanir J, Cohen B (2015) Design and implementation of TeleAdvisor: A projection-based augmented reality system for remote collaboration. In: Computer Supported Cooperative Work (CSCW): An International Journal, vol. 24, no. 6, pp. 527–562. https://doi.org/10.1007/s10606-015-9232-7
115. Jimeno-Morenilla A, Sanchez-Romero JL, Salas-Perez F (2013) Augmented and virtual reality techniques for footwear. In: Computers in Industry, vol. 64, no. 9, pp. 1371–1382. https://doi.org/10.1016/j.compind.2013.06.008
116. Liu YZ, Pang XN, Jiang S et al (2013) : Viewing-angle enlargement in holographic augmented reality using time division and spatial tiling. In: Optics Express, vol. 21, no. 10, pp. 12068–12076. https://doi.org/10.1364/OE.21.012068
117. Li G, Lee D, Youngmo J (2016) Fourier holographic display for augmented reality using holographic optical element. In: Proceedings of the Conference on Advances in Display Technologies VI, EB 18, 2016, San Francisco, USA, vol. 9770, Article Number 97700D. https://doi.org/10.1117/12.2211975
118. Abhishek MT, Aswin PS, Nihal CA (2018) Virtual Lab Using Markerless Augmented Reality. In: Proceedings of IEEE International Conference on Teaching Assessment and Learning for Engineering, DEC 04–07, 2018, Wollongong, AUSTRALIA, pp. 1150–1153
119. Hansson O, Nadum O (2019) Model based operator instructions using AR-technology, Master thesis, Department of Industrial Materials Science, Chalmers University of Technology, Gothenburg, Sweden. https://hdl.handle.net/20.500.12380/300753. Accessed 16 November 2022
120. Neges M, Koch C, Konig M et al (2017) Combining visual natural markers and IMU for improved AR based indoor navigation. Adv Eng Inform 31:18–31. https://doi.org/10.1016/j.aei.2015.10.005