Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 136 (2025) 266–271

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Challenges and Requirements for Augmented Reality in Industrial Assembly Systems

Dennis Keiser[a]*, Dario Niermann[a], Christoph Petzoldt[a], Michael Freitag[a,b]

[a]*BIBA – Bremer Institut für Produktion und Logistik GmbH at the University of Bremen, Hochschulring 20, 28359 Bremen, Germany*
[b]*University of Bremen, Faculty of Production Engineering, Badgasteiner Straße 1, 28359 Bremen, Germany*

* Corresponding author. Tel.: +49 (0)421 218-50183. *E-mail address:* ked@biba.uni-bremen.de

Abstract

In industrial assembly, there are still many manual processes with highly complex tasks and processes. In order to ensure quality and performance, informational assistance systems that support workers during the assembly process have been state of the art for decades. Typically, one-dimensional output technologies such as simple screens are used. However, Augmented Reality (AR) offers various opportunities for better, human-centered information provision. Despite these advantages, AR systems are rarely used in industrial assembly. This paper examines therefore the necessary requirements for successful AR implementation and explores current challenges. The results highlight potential AR applications in assembly and outline the conditions that need to be considered for a successful implementation. We identify 10 requirements for information devices, 6 different types of information devices and 5 different assembly system types for an assessment. We rate every device based on the requirements for each assembly system type. Additionally, we weigh all requirements for each assembly system type, and then calculate the summed rating for each device. Results show that displays are superior to AR devices, which aligns with the current industrial usage. Based on our assessment, we identify several requirements that need to improve for AR to be increasingly used in industrial applications.

Keywords: Assembly; Requirements; Assistance Systems; Augmented Reality;

1. Motivation

Due to the increasing variety of variants along with high requirements for quality and flexibility, industrial assembly is under significant pressure to innovate [1, 2]. This affects all types of assembly system types, which can be categorized into manual, hybrid, and automated systems [3]. Within these system types, the role of humans remains important despite growing efforts towards automation [4]. However, the role of employees varies depending on the degree of automation: In manual and hybrid assembly systems, employees continue to be a central productivity factor, performing typical assembly tasks. This is often due to the complex handling and assembly operations combined with low production volumes, where automation is often not feasible. In automated assembly systems, the role is different: Here, tasks include maintenance, repair, and inspection of the assembly systems. Across all roles, humans play an important role in industrial assembly and they need information to carry out the tasks. However, the purpose of the information, the type of information, and the technologies used differ depending on the type of the assembly system [5]. In manual and hybrid assembly systems, the focus of information delivery is on supporting the assembly process. The goal is to guide employees through the assembly process [6]. These systems, referred to as informational assistance systems, have been standard in assembly for decades and are widely used in industry [7]. Information is typically provided via simple screens or sometimes projectors [4]. In automated assembly systems, the function of information delivery is to display the system status and further support error handling. Figure 1 provides an overview of the types of assembly systems and the role of humans within these systems.

10.1016/j.procir.2025.08.047

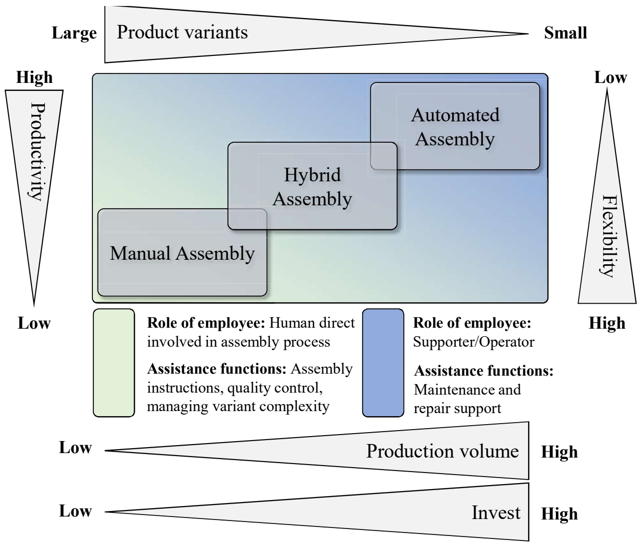

Figure 1: Overview of different assembly system types including the role of humans and information assistance systems [based and adopted on 3]

In both application areas, Augmented Reality (AR) has promised new functions, improved human-machine interaction, and ultimately higher productivity in assembly for years [8]. However, in industrial assembly practice, traditional assistance systems are still being used. The AR technology offers great potential, as it enables direct interaction between virtual and real objects, allowing information to be provided in a highly targeted manner [9, 10]. This is particularly advantageous in complex environments such as assembly. The discrepancy between the high potential of AR and its still limited use in industrial assembly motivates this paper, which seeks to identify current challenges for AR applications in assembly and derive specific requirements.

The paper is structured as follows: The next chapter presents the state of the art. Additionally, previous work on the challenges and requirements of AR in various industries and application fields are reviewed. Chapter 3 builds on this to derive the requirements for AR in assembly and includes an evaluation of different devices. Chapter 4 presents the current challenges and enabling requirements for AR in industrial assembly. This paper ends with Chapter 5.

2. Related work

2.1. *Information assistance systems in assembly processes*

Informational assistance systems provide information throughout the assembly process. These systems contribute to increasing work productivity and shortening training times for new products or employees [11]. The core of all informational systems is the provision of specific assembly instructions. Standard assembly instructions are considered as a crucial factor in industrial assembly to ensure high process reliability and thus, consistent product quality [12]. Due to the various requirements and conditions in assembly, there are many different integration and implementation examples for typical informational assistance systems. Additionally, other functions such as pick-by-light and camera-based quality control are integrated into these systems [4]. In summary, informational assistance systems are a proven technology in assembly and have been part of the industry standard for decades. However, significant innovations regarding the human-machine interface have not yet arrived in practice. Instead, implemented innovations tend to focus on improved integration into companies' IT systems and the use of industrial image processing to enable, for example, quality control or automatic process approvals.

2.2. *Augmented Reality in industrial assembly*

By overlaying the real world (assembly area and component) with the virtual world (assembly instructions), precise instructions can be provided to the employee. Additionally, dynamic assembly instructions can be enabled, such as displaying 3D representations of components [13]. Furthermore, the employee can dynamically interact with the system, performing process approvals or accessing more detailed drawings through gesture control. This possibility for dynamic interaction between humans and devices is huge advantage to AR applications and can lead to improved user-friendliness and thus higher acceptance of the technology. Various devices are available for implementing AR applications, which can be roughly divided into three categories: First, handheld devices like tablets and smartphones. Second, stationary systems that combine a depth camera and projector to enable in-situ projection. The third category includes so-called smart glasses or head-mounted displays (HMDs). These are the most commonly used device categories and are typically associated with AR [14].

2.3. *Preliminary work regarding challenges of AR*

The challenges related to the use of AR have frequently been the subject of different papers [15–19]. Depending on the application field and industry, different analyses and findings are published. In education, challenges regarding the use of AR were reported over a decade ago and is still part of current research [16, 18, 19]. Specific challenges in education, such as the pedagogically correct use of the technology and adaptation to the user's learning process, are not directly transferable to other industries. However, the underlying causes of these challenges, such as the need for process adaptation or cognitive overload of users, can indeed be applied to other sectors. These challenges can also be observed in logistics and are further expanded by additional topics like health and safety, costs, and data protection issues [15]. The challenges in assembly are similarly specified and have been described, among others, by the following authors: [13, 20]. The challenges can generally be categorized into technical and organizational aspects. The technical category includes issues related to hardware and software, such as the weight of HMDs. In the organizational category, high costs are an example of a challenge.

3. Assessment of AR technology in industrial assembly

3.1. *Requirements for informational assistance systems*

In order to evaluate AR technology for use in industrial assembly, this section first outlines general requirements for informational assistance systems in industrial assembly. These requirements are based on literature related to the identification of requirements for informational assistance systems, as well as general requirements for the use of AR [21, 22]. Furthermore, the challenges identified earlier are taken into account, and the authors' experiences from previous research projects have also contributed to the determination of these requirements. The results are shown in Table 1.

Table 1: Identified general requirements for all types of information systems in industrial assembly; including AR devices.

#	Requirement	Description
1	Ergonomics	Physical ergonomics (such as screen placement and HMD weight) and the ergonomics (According to IS0 9241) of the human-machine interface (HMI) are important considerations.
2	Setup Efficiency	The initial setup time of the informational assistance system is highly relevant in assembly, and should be as short and intuitive as possible.
3	Cost Efficiency	Informational assistance systems are investment objects for companies. The investment must be reasonable, and thus costs should be kept low.
4	Information Variety	The system should offer various options for information delivery (2D, 3D, projection into the workspace, sounds, etc.). Therefore, the method of delivery should be as flexible as possible.
5	Adaptability	After the initial setup of the assistance system, changes may be necessary in assembly due to new product variants or adjustments. These modifications should be implemented as quickly and easily as possible.
6	Accuracy	The information should be displayed as accurately as possible in terms of time and location, ensuring seamless integration into the process. Additionally, the information should be simple to understand.
7	Reliability	The technical availability of the assistance system must be as high as possible, meaning that errors or failures should occur as infrequently as possible.
8	Mobility	The mobility of the devices should be maximized to allow continued use in cases such as adjustments to the assembly layout or the operation of more than one assembly station.
9	Supervision & Feedback	There should be options for manual or automatic process approvals, and integration of object detection for quality assurance.
10	Hands-Free	It should also be ensured that the assistance system can be used without having to hold a device in hand.

In total, 10 requirements have been identified, which are generally applicable to informational assistance in industrial assembly. However, depending on the specific use case and context, the importance of each requirement can vary significantly. In addition, organizational requirements such as data security, regulations regarding data protection, and occupational safety may be relevant in practice [23].

3.2. *Devices for information assistance in industrial assembly*

For the design and implementation of informational assistance, various media and devices are available in assembly. Depending on the application case and context, a selection must be made. Assembly instructions are still often provided on paper, without the need for an interface to IT systems at the workplace. This is especially true for small and medium-sized enterprises, as they often lack the necessary expertise and investment resources. However, driven by digitalization in recent decades, an increasing number of digital assistance systems are being introduced in assembly. Traditional systems with fixed screens at the workstation are part of the industry standard and are very popular. If a mobile device is required, tablets can be used as digital device. These classic forms of human-machine interfaces (HMI) are well tested and have a high acceptance among users. The third category includes AR devices. Initially, mobile devices like tablets and smartphones can be mentioned. In addition, there are light projectors used in research and industry that can provide information in the workspace through in-situ projection. These stationary systems have been particularly tested in manual assembly. The last group consists of smart glasses and head-mounted displays (HMDs), which combine high flexibility with the ability to work with both hands. Figure 2 provides a summary of all the described devices.

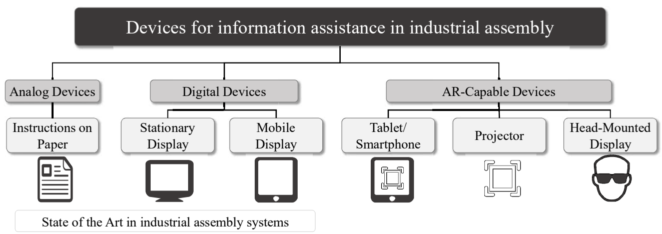

Figure 2: Overview of different possible devices and devices for information assistance in industrial assembly

3.3. *Suitability assessment of devices in industrial assembly*

Section 3.2 demonstrates that various technologies and devices can be used for informational assistance in assembly. These technologies can be seen as competing with one another and are suitable for use in assembly to varying degrees based on their characteristics and the specific context. Starting from the initial research question of why AR technology has not yet been applied in industrial assembly, this chapter evaluates and compares the different technologies available from Section 3.2. We use the 10 requirements specified in Table 1 for this assessment. With the goal of conducting a broadly applicable evaluation while still capturing the heterogeneity of assembly, the assessment is carried out for the following types of assembly systems:

1. Manual stationary assembly
2. Manual mobile assembly
3. Hybrid assembly
4. Automated assembly

For the evaluation, we calculate an applicability score for each technology to each assembly system type. For that, we use the following:

- 10 requirements, further indexed with $r = 1, \ldots, R$
- 6 device types further indexed with $d = 1, \ldots, D$
- 4 assembly system types further indexed with $a = 1, \ldots, A$

First, we evaluate how well each device satisfies each requirement and assign a score from 1 to 5, with 5 being the best. The evaluation is based on expert knowledge and various project experience of the authors. Results are shown in Table 2 in a $R \times D$ matrix further called E.

Table 2: Evaluation matrix $\boldsymbol{E}$ with evaluations for how well a device satisfies a requirement based on the current industry standard. Values between 4 and 5 are highlighted. Based on expert knowledge.

Evaluation *E*	**Device Type**					
Requirement	Paper	Static Display	Mobile Display	HMD	AR-Tablet	Light Projector
Supervision & Feedback	1	4	4	3	3	1
Ergonomics	3	4	4	2	3	5
Setup Efficiency	5	4	4	2	2	2
Cost	5	4	3	2	2	2
Variety	1	3	3	5	5	2
Adaptability	4	4	4	1	1	3
Accuracy	2	4	4	4	4	4
Reliability	5	5	4	2	2	4
Mobility	5	1	3	5	4	1
Hands-Free	2	5	4	5	1	5

We assess paper sheets as generally easy to set up, cost-effective, and reliable. However, they do not provide information variety, adaptability, or feedback mechanisms. Static and mobile displays strike a good balance between setup and cost efficiency, while offering adequate feedback (through touch or keyboard), ergonomics, and reliable information presentation. Nonetheless, these displays are limited in terms of extended supervision, feedback options, and advanced 3D information capabilities. AR devices, while able to enhance the capabilities of traditional displays, currently fall short in terms of setup efficiency, cost-effectiveness, and reliability according to industry standards. HMD are especially suited for manual assembly because of their potential hands-free usage and the easy possibilities to show information.

Next, we define the importance of each requirement for each assembly system type, by assigning a weight W_{ra} between 1 and 9, with 9 being very important and 1 being not important. Each weight is stored in a $R \times A$ Matrix W.

Table 3: Weight matrix W for each assembly system type and requirement. Weights between 7 and 9 are highlighted. Based on expert knowledge.

Weights *W*	**Assembly System Type**			
Requirement	Stationary Manual	Mobile Manual	Stationary Hybrid	Automatic Assembly
Supervision & Feedback	7	7	5	3
Ergonomics	4	4	3	2
Setup Efficiency	4	4	2	1
Cost	3	3	2	1
Variety	5	7	8	5
Adaptability	5	5	7	1
Accuracy	7	7	8	3
Reliability	3	3	3	3
Mobility	1	9	1	6
Hands-Free	9	9	7	3

We used the value range between 1 and 9 to highlight very important requirements over less important ones, while still being able to distinguish between assembly system types. Very important for example is the hands-free requirement for all assembly types where humans need to operate with their hands. Cost is a lower rated requirement overall, because although important, it does not hinder or even disable the assembly process. We further calculate the sum of the weights over all requirements so that we can later norm the results. This gives a norm factor for each assembly system type:

$$n_a = \sum_{r=1}^{R} W_{ra} \quad (1)$$

To get an applicability score s_{tu} for each device and assembly type, we calculate

$$s_{da} = \frac{1}{n_a} \sum_{r=1}^{R} E_{dr} * W_{ra}, \quad (2)$$

which results in the $A \times D$ applicability-score matrix S. The results of this calculation are presented in Table 4.

As the scores suggest, both the display and the HMD are well-suited for nearly all assembly system types. The display performs best overall, except in the case of automatic assembly, where the HMD rates highest. In the current industry standard, the display combines cost and setup efficiency with sufficient adaptability, information variety, and ergonomic interaction with the worker, which is why it is so widely used. In the current standard, the HMD and AR tablet fall slightly short in a few areas, making display solutions the preferred choice for most assembly system types. The light projector, while scoring lower overall, is not inherently a poor technology; rather, it does not meet enough requirements to be a standalone solution. However, it serves as a valuable informational supplement to the display or paper.

Table 4: Applicability-score matrix *S* based on the current industry standard. The two best technology for each assembly system type are highlighted.

Current Applicability-scores *S*	**Device Type**					
Assembly System Type	Paper	Static Display	Mobile Display	HMD	AR-Tablet	Light Projector
Stationary Manual	2,7	**4,1**	3,8	3,3	2,6	3,2
Mobile Manual	3,0	3,6	**3,7**	3,6	2,9	2,8
Stationary Hybrid	2,6	**4,0**	3,8	3,3	2,8	3,2
Automatic Assembly	3,0	3,4	3,6	**3,8**	3,2	2,7

4. Current challenges and enabling requirements for AR devices in industrial assembly

The analysis of the requirements (Table 2) shows that there are various challenges for AR devices in the current industry standard, which result in displays being the superior solution. To be a viable replacement for displays, AR technology needs to be improve on a few key technologies. In the following, we analyze the current technological standard and research and build a forecast on how AR technology will improve in future. For functions like supervision and feedback, there is still a lack of high-performance cameras and sensors on AR devices to implement necessary features such as object detection with the devices. Furthermore, poor ergonomics, especially with head-mounted displays (HMDs), leads to low acceptance among users. Generally the weight of HMDs is still too high, ranging from 250 g to 850 g [20]. However, new additions as the Smart Glass XREAL Air Ultra, available since 2024, weight only 80 g [24]. The cost of the hardware currently ranges from 500 USD to 4000 USD, but is constantly decreasing. Lastly, the current battery hours are mostly not sufficient for a full assembly shift. However, general improvements in battery life are expected.

At the software level, several missing or underdeveloped features have been identified. First, state-of-the-art object recognition is not yet fully capable of detecting and addressing objects in assembly effectively. Additionally, localization mapping remains challenging, which effects the system's overall precision. Furthermore, the Human-Machine Interface (HMI) is still lacking; there are no clear guidelines in place to ensure optimal usability and interaction, highlighting the need for further improvements in this area.

Based on our research on current AR solutions and their trends, we forecast several improvements on the hard- and software level for AR devices.

As highlighted above, AR devices are becoming lighter, more robust, and increasingly ergonomic. Sensory updates, such as advancements in hand tracking, cameras, and world positioning, are also steadily improving. Based on these developments, we propose the following forecast for our requirement evaluation.

First**, ergonomics** are expected to improve from a rating of 2 to 3 for AR head-mounted displays (HMDs), driven by continuous hardware improvements that make the devices more comfortable and suitable for extended use. In terms of **supervision**, we anticipate an increase from 3 to 4 for both HMDs and tablets, placing them on par with traditional display systems, as more advanced sensors and feedback mechanisms are integrated.

Regarding **setup efficiency** and **cost**, we set AR technology to improve from a rating of 2 to 3. However, these will remain slightly worse than display systems, which are simpler to set up and generally more cost-effective. A significant leap is expected in **adaptability**, with a forecasted improvement from 1 to 4 for both HMDs and tablets. Emerging software solutions are set to greatly enhance the flexibility and customization of AR devices, bringing them to the same level as current display technologies.

The **accuracy** of AR systems is also projected to rise from 4 to 5, as advancements in software and sensors will allow AR devices to surpass display-level performance in providing precise information. Finally, we anticipate a boost in **reliability**, from 2 to 4, as ongoing developments in both hardware and software will make AR devices as dependable as traditional display systems.

Using these forecasts for future AR technology, we calculate a new applicability score and compare them again. The applicability matrix is shown in Table 5. It shows that with these forecasted evaluations; HMD becomes the overall best solution for all assembly systems. Although close contenders are still displays, the score differences are quite high, with highest being mobile manual assembly, followed by stationary hybrid.

Table 5: Applicability-score rating as forecasted by our analysis. The two best device types are highlighted for each assembly system type.

Forecasted Applicability-score *S*	**Device Type**					
Assembly System Type	Paper	Static Display	Mobile Display	HMD	AR-Tablet	Light Projector
Stationary Manual	2,7	4,1	3,8	**4,2**	3,5	3,2
Mobile Manual	3,0	3,6	3,7	**4,4**	3,6	2,8
Stationary Hybrid	2,6	4,0	3,8	**4,4**	3,7	3,2
Automatic Assembly	3,0	3,4	3,6	**4,5**	3,8	2,7

5. Discussion and outlook

The evaluation of various information systems shows that conventional displays are preferred due to their current superiority over AR devices. Through our evaluation method, it is shown that specific requirements, such as ergonomics and accuracy, need to be improved to enable a broader adoption of AR in industry. The paper thus provides a solid foundation for the future development of AR in industrial applications. Furthermore, this paper outlines the challenges for AR in industrial applications. With our evaluation and applicability rating, many more calculations and analysis can be conducted. For example, for each requirement, forecasts can be made and calculated applicability scores can be evaluated, looking into the impact of that forecast. Future research can thus be analyzed and the most important aspects to improve AR technology can be identified. Additionally, case studies and expert interviews should be utilized to further validate the requirements for AR systems and develop practical solutions and to improve on the evaluation and weights that we defined. Further to discuss is that AR may be overestimated in certain use cases, while conventional displays might continue to be a viable solution. However, AR technology has a lot of potential for use cases in industrial assembly in future. One promising use case is for example the support of dynamic task allocation in hybrid assembly scenarios.

Acknowledgements

This research has been funded by the Federal Ministry for Economic Affairs and Climate Action of Germany as part of the project "SMART - Dynamic control of collaborative assembly in the digital twin using AR and AI-based situation recognition" (project number 16KN102633).

References

1. Krüger J, Wang L, Verl A, Bauernhansl T, Carpanzano E, Makris S, Fleischer J, Reinhart G, Franke J, Pellegrinelli S (2017) Innovative control of assembly systems and lines. CIRP Ann 66:707–730 . https://doi.org/10.1016/j.cirp.2017.05.010
2. ElMaraghy H, ElMaraghy W (2016) Smart Adaptable Assembly Systems. Procedia CIRP 44:4–13 . https://doi.org/10.1016/j.procir.2016.04.107
3. Lotter B, Wiendahl H-P (2012) Montage in der industriellen Produktion, 2. Auflage. Springer Verlag, Berlin, Heidelberg
4. Keiser D, Petzoldt C, Beinke T, Vogler H, Freitag M (2021) Mitarbeiterzentrierte Assistenzsysteme für die manuelle Montage - Systematische Evaluation von Montageassistenzsystemen. Ind 40 Manag 37:11–15
5. Hinrichsen, Sven; Riediger, Daniel; Unrau A, Hinrichsen S, Riediger D, Unrau A (2016) Assistance Systems in Manuel Assembly. In: Production Engineering and Management. Proceedings 6th International Conference. 29.09. - 30.09.2016 in Lemgo, Germany. pp 3–14
6. Fink K, Ziegler A, Härdtlein C, Berger C, Daub R (2024) Assessing the Human Competence and Individual Support Level in Manual Assembly through Cognitive Assistance Systems. Procedia CIRP 126:811–816 . https://doi.org/10.1016/j.procir.2024.08.263
7. Bornewasser M, Hinrichsen S (2020) Informatorische Assistenzsysteme in der variantenreichen Montage - Theorie und Praxis. Springer Verlag, Berlin
8. Mark BG, Rauch E, Matt DT (2021) Worker assistance systems in manufacturing: A review of the state of the art and future directions. J Manuf Syst 59:228–250 . https://doi.org/10.1016/j.jmsy.2021.02.017
9. Quandt M, Freitag M (2021) A Systematic Review of User Acceptance in Industrial Augmented Reality. Front Educ 6:1–17 . https://doi.org/10.3389/feduc.2021.700760
10. Carmigniani J, Furht B, Anisetti M, Ceravolo P, Damiani E, Ivkovic M (2011) Augmented reality technologies, systems and applications. Multimed Tools Appl 51:341–377 . https://doi.org/10.1007/s11042-010-0660-6
11. Petzoldt C, Keiser D, Beinke T, Freitag M (2020) Functionalities and implementation of future informational assistance systems for manual assembly. Commun Comput Inf Sci (S-BPM-ONE 2020) submitted
12. Papetti A, Ciccarelli M, Claudio M, Germani M (2023) How to provide work instructions to reduce the workers ' physical and mental workload. Procedia CIRP 120:1167–1172 . https://doi.org/10.1016/j.procir.2023.09.143
13. Wang Z, Bai X, Zhang S, Billinghurst M, He W, Wang P, Lan W, Min H, Chen Y (2022) A comprehensive review of augmented reality-based instruction in manual assembly, training and repair. Robot Comput Integr Manuf 78:102407 . https://doi.org/10.1016/j.rcim.2022.102407
14. Dey A, Billinghurst M, Lindeman RW, Swan JE (2018) A systematic review of 10 Years of Augmented Reality usability studies: 2005 to 2014. Front Robot AI 5: . https://doi.org/10.3389/frobt.2018.00037
15. Rejeb A (2019) The Challenges of Augmented Reality in Logistics: A Systematic Literature Review. World Sci News 134:281–310
16. Wu HK, Lee SWY, Chang HY, Liang JC (2013) Current status, opportunities and challenges of augmented reality in education. Comput Educ 62:41–49 . https://doi.org/10.1016/j.compedu.2012.10.024
17. Zhan T, Yin K, Xiong J, He Z, Wu ST (2020) Augmented Reality and Virtual Reality Displays: Perspectives and Challenges. iScience 23:101397 . https://doi.org/10.1016/j.isci.2020.101397
18. Akçayır M, Akçayır G (2017) Advantages and challenges associated with augmented reality for education: A systematic review of the literature. Educ Res Rev 20:1–11 . https://doi.org/10.1016/j.edurev.2016.11.002
19. Iqbal MZ, Mangina E, Campbell AG (2022) Current Challenges and Future Research Directions in Augmented Reality for Education. Multimodal Technol Interact 6:1–29 . https://doi.org/10.3390/mti6090075
20. Danielsson O, Holm M, Syberfeldt A (2020) Augmented reality smart glasses in industrial assembly: Current status and future challenges. J Ind Inf Integr 20:100175 . https://doi.org/10.1016/j.jii.2020.100175
21. Petzoldt C, Keiser D, Beinke T, Freitag M (2020) Requirements for an Incentive-based Assistance System for Manual Assembly. In: Freitag, M., Haasis, H.-D., Kotzab, H., Pannek, J. (eds.): Dynamics in Logistics. Proceedings of the 7th International Conference on Dynamics in Logistics (LDIC 2020). Springer, Cham 2020. pp 541–553
22. Quandt M, Knoke B, Gorldt C, Freitag M, Thoben KD (2018) General Requirements for Industrial Augmented Reality Applications. Procedia CIRP 72:1130–1135 . https://doi.org/10.1016/j.procir.2018.03.061
23. Quandt M, Ait Alla A, Freitag M (2017) Success Factors for the Development of Augmented Reality-based Assistance Systems for Maintenance Services Controller design for vehicle to grid technology View project preInO-Methods and Tools for the Pro-Active Maintenance of Offshore Wind Turbine Gener
24. XREAL (2024) XREAL Air 2 Ultra. https://eu.shop.xreal.com/de-de/products/xreal-air-2-ultra