CHALLENGES OF USING AUGMENTED REALITY TO SUPPORT AN EFFICIENT AND ERROR-FREE ASSEMBLY IN COMPLEX VARIANT ENVIRONMENTS

Dausch, Valesko Cedrik (1);
Roth, Daniel (1);
Kreimeyer, Matthias (1);
Bohr, Sebastian (2)

1: University of Stuttgart;
2: MAN Truck & Bus SE

ABSTRACT

As part of the digital transformation towards Industry 4.0, the tasks of staff on the shop floor are changing. Despite increasing automation, complex assembly steps still have to be carried out by humans, especially when it comes to complex products rich in variants, whose assembly cannpt be fully automated for various reasons. Due to increasing individualization and the steadily growing complexity of products, providing the right information at the right time and in the right place is becoming more important. In this context, the visualization of information via novel technologies such as augmented reality plays a crucial role towards an efficient and error-free production process. This paper compiles existing challenges when using augmented reality as a visualization form for an assistance system. On the one hand, the challenges found originate from a systematic literature review and are organized according to predefined categories. On the other hand, these challenges are complemented and compared through findings gained from expert interviews, which are conducted with employees of two European commercial vehicle manufacturers in the field of production. The analysis of the two methods highlights the need for further research.

Keywords: Visualisation, Industry 4.0, Augmented Reality, Assembly, Information management

Contact:
Dausch, Valesko Cedrik
University of Stuttgart
Germany
valesko.dausch@iktd.uni-stuttgart.de

Cite this article: Dausch, V. C., Roth, D., Kreimeyer, M., Bohr, S. (2023) 'Challenges of Using Augmented Reality to Support an Efficient and Error-Free Assembly in Complex Variant Environments', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.86

1 INTRODUCTION AND MOTIVATION

Despite the trend towards increasing automation, manual assembly processes will still be carried out by assembly personnel for complex or variant-rich products (Alves et al., 2019; Khuong et al., 2014; Mattsson et al., 2018). In manual assembly processes, high process reliability can be achieved through good worker guidance. Thus being crucial to increase product quality while reducing assembly time as well as the manufacturing and the error costs.

New technologies that offer completely new forms of visualization and interaction with the staff seem to supply a remedy to this end, but have not yet been sufficiently mastered in industrial practice, could be applied widely. Here, the focus is on augmented reality (AR) according to (Erboz, 2017) as a driver of digital transformation in the context of Industry 4.0. This technology is not only capable of providing good process guidance in order to increase quality, but could also possibly validate the processes carried out by giving direct feedback (Alves et al., 2021) and provide support in other process-relevant activities via the interactive provision of information. Furthermore, it can be assumed that shop floor staff will take on more and more diverse tasks with a higher degree of responsibility (Danielsson et al., 2018; Holm et al., 2016). Cognitive support, such as AR, will thus be required according to (Romero et al., 2016). This gives rise to the question to what extend a central overview of the main challenges that originate when AR is used in a standardized way for displaying relevant process information in an industrial environment as part of an assembly assistance system already exists. This issue not only relates to technological challenges for the introduction of AR technology in companies, but also addresses questions about the flow of data within devices in the Internet of Things (IoT).

2 DEFINITIONS CONSIDENIG AUGMENTED REALITY

To further refine the scope of the challenges found in the literature review in section 4, it is necessary to explain the terms used in the extended reality (XR) context. XR includes all forms of real-and-virtual combined environments, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) (Fast-Berglund et al., 2018). The classification and delimitation of technologies is based on the reality-virtuality continuum (see Figure 1), which delimits technologies based on their proximity to a real or virtual environment (Milgram and Kishino, 1994). For this paper, MR and AR applications play a particularly important role. In practice, however, it becomes apparent that the delimitation of the two terms MR and AR is more than fuzzy. According to the definition given by (Fast-Berglund et al., 2018; Gong et al., 2021), AR applications only add information in addition to the real world. MR rather provides the possibility for real and virtual content to interact with each other (Rokhsaritalemi et al., 2020). In the research, it has been found that MR systems are often referred to as AR systems, contrary to the definition given above. For the rest of this paper, only the term AR will be used (including MR & AR). In VR, users are immersed in a fully virtual environment and cannot visually recognize the real world around them (Fast-Berglund et al., 2018). Although newer VR devices may offer the option of what is called a pass-through mode (e.g. Metaquest Pro Headset from Meta), where content is added to a camera capture of the real world (Xiao et al., 2022), VR was not considered as part of this research since there are not many devices available that support this feature and because VR is mostly used in product development and not in productive assembly.

Figure 1. Reality–virtuality continuum (Milgram and Kishino, 1994)

AR can be further divided into 3 types: hand-held, head-worn, and spatial AR (van Krevelen and Poelman, 2010). The end device is the crucial factor behind this distinction. For example, hand-held AR uses a smartphone or tablet (Shiratuddin et al., 2014), head-worn AR uses a head-mounted display (HMD) (Azuma, 1997) such as a Microsoft HoloLens or Google Glass, and spatial AR uses a projector or monitor to display information (Azuma et al., 2001). In this research paper, there is no limitation regarding the end devices to allow for a comprehensive analysis of challenges found in the AR context.

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

3 STRUCTURE & METHODOLOGY

This paper is part of a research project dealing with the design of digital assistance on the shop floor as well as the implementation of a modern assistance system at a commercial vehicle manufacturer.
Within this paper, the methods used to develop the results as well as the focusing of the scope are presented in section 3. The results are then presented and categorized in section 4 & 5 and discussed in section 6. Section 7 summarizes the paper and provides an outlook on further research needs. The objective of the paper is to list the most relevant challenges that exist when using AR in a modern assistance system whose scope goes beyond guiding assembly information.
In this paper, two methods are used to identify the challenges of AR-supported worker guidance by means of an assistance system. First, the challenges found via a systematic literature review are presented. In a second step, further challenges identified during interviews with production experts are also presented. This allows the scientific view from the literature research to be compared with the knowledge and needs found within the industry, thus providing a holistic picture of the challenges.

3.1 Literature review

The systematic literature review was carried out as follows:
1. Identifying relevant keywords and building search strings
2. Searching two databases for literature to review
3. Filtering the results with several criteria
4. Detailed analysis of the contributions found to be relevant

The steps described above were carried out in September 2022 on the following databases: "Science Direct" and "IEEE Xplore" The initial search found 980 results. After adding filters, e.g. research domain, the amount dropped to 354. The analysis of title keywords and abstracts resulted in 124 papers of interest, of which 41 were found relevant for this paper after reading the full paper (see Figure 2).

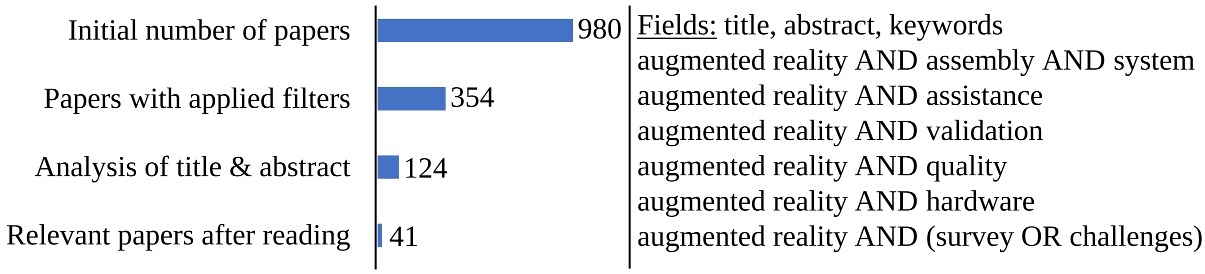

Figure 2. Analysed papers in the systematic literature review

3.2 Expert interviews

The participants of the interview are employees of two European commercial vehicle manufacturers that are mainly involved in the digital transformation of production in their daily work. The interviews did not focus exclusively on worker assistance using AR, but also included questions on general trends of production in the context of Industry 4.0. The purpose of such an approach is to provide a broader perspective in order to ascertain the actual needs and not to restrict the focus of AR to an early stage.
Before the 30-minute interviews, a short introduction was given to address the context of the questions. The interviews were conducted in guided form and subsequently evaluated. The results of the interviews are collectively presented in section 5. In each interview, participants were asked the following questions:

- What do you think are the most important technologies for the production of the future? Name up to five and provide reasons for your answer!
- What are the added values for your employer through the introduction of these technologies?
- What, in your opinion, are the biggest challenges to the introduction of these technologies into your company?
- Where do you think immediate action is needed with respect to these technologies to increase the quality of your employer's products?
- How can shop floor staff benefit from these technologies?
- How could AR generate added value in this context?
- What information should be provided to shop floor staff in the assembly line?

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

The various ages, levels of professional experience, sectors, and shares of activities relating to digital transformation in the participants' everyday work are shown in Figure 3. In total 11 interviews were conducted

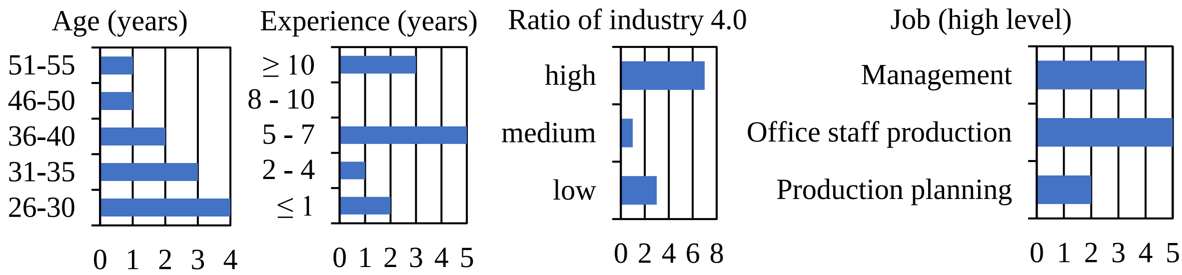

Figure 3. Experts age, department, experience, and ratio of industry 4.0 topics

4 CHALLENGES FOUND THROUGH SYSTEMATIC LITERATURE REVIEW

Today, manual processes are mostly provided to shop floor staff via descriptive instructions in step-based form (digital or paper-based) in order for these workers to learn processes or to execute them according to the specifications (Alves et al., 2019). Usually, there is no feedback for the staff about the correct execution of the assembly steps (Alves et al., 2019). For this reason, it seems useful to use AR applications for the guidance of workers and the verification of process execution. According to (Alves et al., 2019; Bottani and Vignali, 2019), the increasing number of publications on this topic also increases the interest in AR, while (Zubizarreta et al., 2019) state that companies are also interested in introducing new services as well as new capabilities through this technology. During a survey in (Holm et al. 2016) it was found that, on the management level of companies, AR is seen as a necessary future technology. Furthermore, the extensive research of (Souza Cardoso et al., 2020) shows that the support of manual assembly processes is by far the largest application area for the use of AR. Nonetheless this potential and the great scientific interest in AR, there have been few productive applications to date and there is a lack of research contributions for implementing the technology in a productive expansion stage (Gong et al., 2021; Jetter et al., 2018; Szajna et al., 2020; Uva et al., 2018). In summary, AR applications are not yet widely used in industrial settings. The reasons behind this low level of use are manifold (Gattullo et al., 2022) and will be presented separately according to the following four categories as a result of the research:

- Data management
- Process validation
- Hardware
- Interaction

4.1 Challenges regarding data management

The research of (Alves et al., 2021) shows that scientific publications from the years 2013 to 2021 that deal with AR assistance for workers focus on quality control or the provision of logistical information in only a subordinate role. For example, (Wang et al., 2016) states that the focus on step-by-step process instruction, especially in the area of assembly assistance, neglects important concerns such as displaying the remaining assembly time for a job. According to a survey of in-store staff, information such as confirming the correct tightening torque of bolts, the current assembly time and identifying potential errors are critical for workers during engine assembly (Danielsson et al., 2018). In further research, Alves states in (Alves et al., 2019) and (Alves et al., 2021) that a shortcoming of existing assistance solutions is also the lack of feedback regarding the executed process. Alves refers to the lack of feedback in AR systems as an open loop characteristic which needs to be addressed. To achieve the capabilities described above, it is necessary to integrate systems and equipment of the production system into the application, to provide real-time access to data on tools such as screwdrivers (Danielsson et al., 2020), and to provide information on quality-critical parameters to be checked. This formulates the efforts regarding tasks such as interconnecting devices and sensors via the IoT that are not currently considered as computing devices (Rosales et al., 2021; Sarhan, 2018). It is also necessary to connect this data to other information regarding the product, which in turn formulates the efforts of a seamless data model to handle order-specific and real-time shop floor data. Currently, printed instructions in particular carry the

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

risk of being outdated without this being noticed (Wilson et al., 2012). Time validity is also relevant for AR instruction according to (Quint and Loch, 2015), since creating and publishing AR content is time-consuming, computationally expensive, and currently cannot be automated. Content creation therefore occurs before an AR experience is consumed by the user and is performed on decentralized computers and in other systems. An end-to-end change process is imperative, as displaying incorrect content also decreases user confidence in the technology.
The findings presented above lead to the following challenges:

- C1: Include capabilities exceeding step-by-step instructions
- C2: Establish the access to and visual display of IoT data
- C3: Create data model to link IoT data from the shop floor to specific orders
- C4: Feedback during process
- C5: Seamless change process to keep time validity

4.2 Challenges regarding process validation

Closing the open loop characteristic described in section 4.1 implies that verification of process execution in conjunction with context understanding must be given within an AR application. (Ziaee and Hamedi, 2021) state that most assembly errors are due to procedural errors and caused by negligence (Neumann and Majoros, 1998). According to (Ziaee and Hamedi, 2021) the errors are caused by the fact that not all important information can be retrieved centrally at the right time for the worker (Alarcon et al., 2020) and automatically at the right station with low latency (Wang et al., 2016). This is necessary for validating if a step was carried out correctly by the worker and therefore increasing the usability of AR systems (Alves et al., 2021). In the event that a process is validated not by shop floor staff themselves, but instead via the assistance system, additional equipment is needed and also requires integration. Studies that examine the possibilities of automatic process validation using context-aware AR systems still require many additional sensors as described e.g. in (Bellalouna, 2022; Gorecky et al., 2011). Besides, they are limited in complexity and difficult to transfer to real industrial assembly scenarios. For example, (Werrlich et al., 2017) emphasize that many studies on AR-based assistance systems assume simplified assembly situations such as the assembly of LEGO® blocks or simple geometries. This leads to restraints when using AR in reality. For example, (Wang et al., 2016) concluded that limitations of AR systems prevent the use of complex assembly processes. (Quint and Loch, 2015) also state that AR is not suitable for complex processes. On the other hand, (Radkowski, 2015) states that AR only adds value for sufficiently complicated operations. In this case, this statement is to be understood in terms of providing instructional content. Nevertheless, the dilemma for the use of AR from a user perspective is manifested here. The technology is only suitable for a certain range of complexity, otherwise no added value is generated, or the creation of the information content becomes too effortful (see Figure 4).

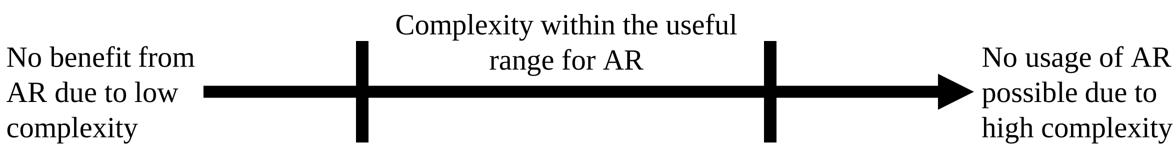

Figure 4. Complexity dependency of AR

Despite the industrial demand, many investigations and projects remain at the proof-of-concept stage (Jetter et al., 2018). This begs the question as to how much complexity in real industrial settings can currently be handled. The findings presented above lead to the following challenges:

- C6: Enable shop floor information access
- C7: Context awareness
- C8: Find right level of complexity for industrial applications

4.3 Challenges regarding hardware

The most commonly used AR device in studies is an HMD (Gattullo et al., 2022; Souza Cardoso et al., 2020). However, further research shows that the ergonomics of HMDs are currently unsatisfactory, making it unrealistic to use them for several hours a day (Danielsson et al., 2020; Souza Cardoso et al., 2020). In addition to displaying the correct content, as described in section 4.1, the time-synchronous

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

overlay of virtual objects on the real environment is important for user acceptance. A delay can occur both in data acquisition and in the computation or transmission of AR content to or from the visualization device (Orlosky et al., 2017). To solve these issues, high computational power or high data transmission rates are required. If the data is processed locally on the visualization device, ergonomics must be balanced against mobility. However, these points only concern data glasses and mobile devices. Today, smart glasses do not have sufficient computing power (Chatzopoulos et al., 2017; Porcelli et al., 2013; Um et al., 2018). For decentralized computation of AR content, new forms of network technology such as 5G could solve the problem (Lv et al., 2022). Another problem is battery life of mobile devices. For example, the Microsoft HoloLens 2 can only be used for about 2-3 hours with one battery charge (Bitnamic, 2022; Danielsson et al., 2020). The findings presented above lead to the following challenges:

- C9: Ergonomics of HMD
- C10: Battery life of HMD
- C11: Processing power of smart glasses
- C12: Network transfer rates

4.4 Challenges regarding interaction

According to (Azuma, 2016), one of the most important challenges for the establishment of AR is the following:
"How will we establish Augmented Reality as a new form of media, enabling new types of experiences that differ from established media?"
To most people, AR is a (still) unfamiliar form for interacting with data due to the lack of standardized interaction interfaces and low distribution of corresponding applications in the consumer market (Ghazwani and Smith, 2020). Interaction is seen as one of the biggest challenges for the use of AR according to the survey of (Souza Cardoso et al., 2020). For HMDs and projections in particular, there are no standardized control concepts similar to a computer mouse or a touchscreen. Existing gesture controls are not very intuitive and only cover a limited range of functions (Wang et al., 2016). Additionally, the orientation in space has not been sufficiently solved for HMDs as the lack of visualization limitation compared to a monitor poses a problem. This outlines the need for intuitive and standardized operating concepts, which could use gesture or voice control (Billinghurst et al., 2009). However, due to high noise levels or limited mobility when handling parts, even these concepts could only be a limited help for operations during assembly. Additionally, it is important to achieve user acceptance when dealing with the introduction of modern technology. Gamification strategies may therefore be used (Souza Cardoso et al., 2020). The findings presented above lead to the following challenges:

- C13: Intuitive and standardized interaction standards for AR
- C14: User acceptance toward AR

5 COMPARISON OF THE CHALLENGES IDENTIFIED IN THE INTERVIEWS

This section compares the challenges identified in section 4 with the challenges that could be identified during the interviews. A summarized overview is given in table 1. The "Interview" column contains information on how many participants of the interview addressed a challenge. Notable findings from the interviews will also be presented in the following paragraphs. At the beginning of the interview, the participants were asked about key technologies that will shape the future production of their employer. All the following technologies were mentioned with roughly equal frequency:

- Digital Twin
- Robotics
- Artificial Intelligence & Computer Vision
- IoT & Data Connectivity
- Track & Trace
- Augmented & Virtual Reality

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

When it comes to justifying the choice of the technologies, the control of multi-variant products and processes as well as the reliable detection of errors have the highest relevance. The expected added value of digitization was almost exclusively motivated by the increase in product quality, improved efficiency and lower cycle times. On top of that increased process transparency is achieved due to the availability of digital structured data. Among the challenges concerning the introduction of the technologies in the respective company, major emphasis was placed on the substantial one-off effort required for the introduction of new technologies. Furthermore, it was frequently highlighted that sufficient knowledge about the capabilities of new technologies must be available across all hierarchical levels in the respective company in order to be able to make appropriate decisions. For the staff on the shop floor, the respondents mentioned the need for work in improved and more transparent processes, more pleasure at work in a modern working environment, and an increase in ergonomics. The rest of the interview focused on AR technology. In addition to mastering variance and the possibility of presenting direct feedback on process execution, it was outlined that AR could be used throughout the whole assembly process and not just for step-by-step instructions. When asked, two of the respondents justified this by the lack of need for step-by-step instruction after the initial training process. The last question in the interview was designed to identify the necessary information that should be provided to shop floor staff via AR (see Figure 5). In response to requests for further information, it was stated by the interviewer that the information should be provided for a trained worker working at the same assembly station for several months at least.

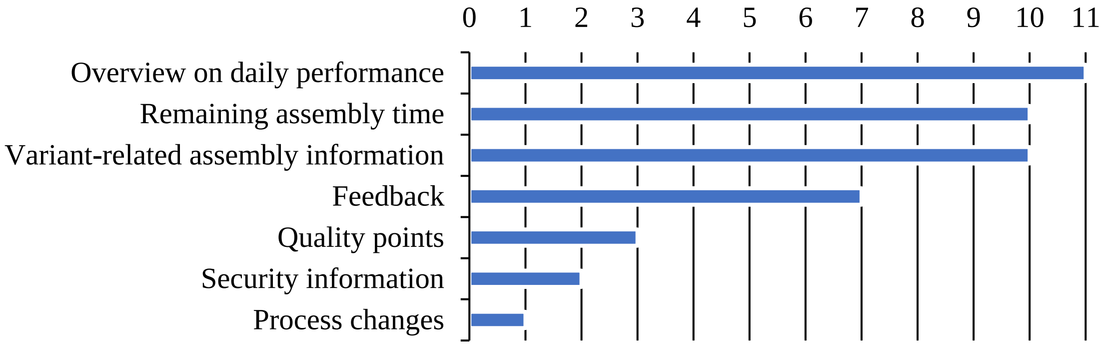

Figure 5. Necessary information to provide to shop floor staff via AR

The aspects with the joint most frequent mentions were an overview of the daily performance, the remaining assembly time, and variant-related assembly information (part numbers, measurements, attributes etc.). In addition to the previous information, direct feedback on whether or not a task was executed correctly was also considered helpful. A note to important quality points as well as safety-relevant information and the notification of changes in the processes were also mentioned, but more rarely.

Table 1. Summary of challenges

No.	Challenge	Interview
C1	Include capabilities exceeding step-by-step instructions	8/10
C6	Enable shop floor information access	6/10
C4	Feedback during process	5/10
C8	Find right level of complexity for industrial applications	5/10
C13	Intuitive and standardized interaction standards for AR	5/10
C3	Create data model to link IoT data from the shop floor to specific orders	4/10
C12	Network transfer rates	4/10
C14	User acceptance toward AR	4/10
C2	Establish the access and visual display of IoT data	3/10
C11	Processing power of smart glasses	2/10
C5	Seamless change process to keep time validity	1/10
C7	Context awareness	0/10
C9	Ergonomics of HMD	0/10
C10	Battery life of HMD	0/10

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

6 DISCUSSION

The first finding to emerge is that technological challenges which raise doubts about the benefits of AR (computing power, battery life, and network transferring speed) are not mentioned in the interviews. Instead, it appears from the interviews that there are challenges relating to the successful application of AR, which relate in particular to the preparation, processing, and collection of data. In addition to robotics, the participants in the interviews raise a particular need for the technologies of IoT and computer vision. All of these technologies will require a solution for the data challenges mentioned above. Furthermore, both literature and interviews point out that the integration of quality checks within the assembly process is necessary and should be included in an assistance system. This is in contrast to most of the implemented applications that have been identified, which focus on giving step-by-step instructions to the worker – and display the assembly information primarily via an overlay of the target state on previously prepared 3D data. In terms of quality checks, both, the literature as well as the interviews highlight the need for workers to be provided with information relating to the time status of an order or the torque of a screwdriver as well as variant-related assembly information. This would improve the information situation and thus the transparency of the process for the workers, regardless of the visualization technology in use. The literature and interviews find that AR may possibly lower the cognitive load. However, there are already numerous publications that consider AR as a visualization form for an assistance system in assembly. But most applications use an HMD. Regarding the poor ergonomics and battery life, these devices are not conducive to standardized industrial use. While the literature also highlights the challenges regarding the user interaction with AR systems, the experts point out that one serious challenge for standardizing this new technology will be the high effort required within companies for primary implementation of a new technology.

7 SUMMARY & OUTLOOK

This paper presents an overview of challenges found in context for the use of augmented reality in a digital assistance system for shop floor staff. First, a systematic literature review was conducted to gather challenges occurring within the industrial use of AR in assembly operations. The challenges identified were sorted into 4 categories and summarized. This was followed by a presentation of the results and challenges identified via the expert interviews. The interviews were therefore not exclusively focused on AR. This approach was chosen to provide a broader view on the topic and therefore the questions addressed general trends of future production as well as the information that needs to be provided to staff on the shop floor. The categorized answers were then compared with the challenges found in the literature. Finally, a mapping was performed to identify overlapping and delimited challenges.

By looking at the results of this paper, it becomes obvious that collecting and publishing data via one central data layer from different sensors and systems is a mandatory prerequisite for a future assembly assistance system. Once all this information is available, intuitive visualization and interaction performed in a new way using AR technology will further optimize the usage of data on the shop floor. The transparency of data origin and use plays just as important a role as rapid processing and context setting in a corresponding system. Reliability, in addition to the rapid availability of data, is a decisive factor for users trust in a gamified system. Further research should focus on defining the functionalities needed in a modern assembly assistance system. Besides the technologies used, it will be equally important to point out how the necessary information and data can be collected in an industrial setting to build the digital shadow of the product and the production system to be consumed in AR. Furthermore, it should be investigated in which form this information can be presented to shop floor staff in real time and how interaction could be carried out. It is important that the design of such a system is focused on the acceptance of the users, as the full benefit of a new assistance system can only be obtained when it is used on a daily basis.

REFERENCES

Alarcon, R., Wild, F., Perey, C., Genescà, M. M., Ruiz, M., Olmos M., and Dubert, D. (2020), "Augmented Reality for the enhancement of space product assurance and safety", *Acta Astronautica*, vol. 168, pp. 191–199, [online] https://doi.org/10.1016/j.actaastro.2019.10.020.

Alves, J. B., Marques, B., Dias, P. and Santos, B. S. (2021) "Using augmented reality for industrial quality assurance: a shop floor user study", *The International Journal of Advanced Manufacturing Technology*, vol. 115, 1-2, pp. 105–116, [online] https://link.springer.com/article/10.1007/s00170-021-07049-8.

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press

Alves, J. B., Marques, B., Oliveira, M., Tiago Araujo, T., Dias, P. and Sousa Santos, B. (2019) "Comparing Spatial and Mobile Augmented Reality for Guiding Assembling Procedures with Task Validation", *19th IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC 2019), Porto, Portugal*, pp. 1-6, [online] https://doi.org/10.1109/ICARSC.2019.8733642.

Azuma, R. (1997) "A Survey of Augmented Reality", *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355-385, [online] https://doi.org/10.1162/pres.1997.6.4.355.

Azuma, R. (2016) "The Most Important Challenge Facing Augmented Reality", *Presence: Teleoperators and Virtual Environments*, vol. 25, no. 3, pp. 234–238, [online] https://doi.org/10.1162/PRES_a_00264

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S. and MacIntyre, B. (2001) "Recent advances in augmented reality", *IEEE Computer Graphics and Applications*, vol. 21, no. 6, pp. 34–47.

Bellalouna, F. (2022) "Use Case of the Application of the Optical-See-Through Augmented Reality Technology in the Engineering Context", *Procedia CIRP*, vol. 106, pp. 3–8, [online] https://doi.org/10.1109/38.963459.

Billinghurst, M., Kato, H. and Myojin, S. (2009) "Advanced Interaction Techniques for Augmented Reality Applications", Shumaker, R. (eds) Virtual and Mixed Reality. VMR 2009. Lecture Notes in Computer Science, vol. 5622, pp. 13–22, [online] https://doi.org/10.1007/978-3-642-02771-0_2.

Bitnamic (2022) Microsoft HoloLens 2: Funktionen und Verbesserungen, bitnamic, [online] https://bitnamic.net/microsoft-hololens-2-funktionen-und-verbesserungen/ [accessed 29 October 2022].

Bottani, E. and 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, [online] https://doi.org/10.1080/24725854.2018.1493244

Chatzopoulos, D., Bermejo, C., Huang, Z. and Hui, P. (2017) "Mobile Augmented Reality Survey: From Where We Are to Where We Go", *IEEE Access*, vol. 5, pp. 6917–6950, [online] https://doi.org/10.1109/ACCESS.2017.2698164

Danielsson, O., Holm, M. and Syberfeldt, A. (2020) "Augmented reality smart glasses for operators in production: Survey of relevant categories for supporting operators", *Procedia CIRP*, vol. 93, pp. 1298–1303, [online] https://doi.org/10.1016/j.procir.2020.04.099.

Danielsson, O., Syberfeldt, A., Holm, M. and Wang, L. (2018) "Operators perspective on augmented reality as a support tool in engine assembly", *Procedia CIRP*, vol. 72, pp. 45–50, [online] https://doi.org/10.1016/j.procir.2018.03.153.

Erboz, G. (2017) "How to Define Industry 4.0: Main Pillars of Industry 4.0", *7th International Conference on Management*, Nitra, Slovakia.

Fast-Berglund, Å., Gong, L. and Li, D. (2018) "Testing and validating Extended Reality (xR) technologies in manufacturing", *Procedia Manufacturing*, vol. 25, pp. 31–38, [online] https://doi.org/10.1016/j.promfg.2018.06.054.

Gattullo, M., Evangelista, A., Uva, A. E., Fiorentino, M. and Gabbard, J. L. (2022) "What, How, and Why are Visual Assets Used in Industrial Augmented Reality? A Systematic Review and Classification in Maintenance, Assembly, and Training (From 1997 to 2019)", *IEEE transactions on visualization and computer graphics*, vol. 28, no. 2, pp. 1443–1456, [online] https://doi.org/10.1109/TVCG.2020.3014614.

Ghazwani, Y. and Smith, S. (2020) "Interaction in Augmented Reality: Challenges to Enhance User Experience", *Proceedings of the 2020 4th International Conference on Virtual and Augmented Reality Simulations*. New York, NY, USA, Association for Computing Machinery, pp. 39–44, [online] https://doi.org/10.1145/3385378.3385384.

Gong, L., Fast-Berglund, A. and Johansson, B. (2021) "A Framework for Extended Reality System Development in Manufacturing", *IEEE Access*, vol. 9, pp. 24796–24813, [online] https://doi.org/10.1109/ACCESS.2021.3056752

Gorecky, D., Worgar, S. and Meixner, G. (2011) "COGNITO: a cognitive assistance and training system for manual tasks in industry", *ECCE 2011 - European Conference on Cognitive Ergonomics*. Rostock, Germany, 24.08.2011, pp. 53-56, [online] https://doi.org/10.1145/2074712.2074723.

Holm, M., Adamson, G., Moore, P. and Wang, L. (2016) "Why I want to be a Future Swedish Shop-floor Operator", *Procedia CIRP*, vol. 41, pp. 1101–1106, [online] https://doi.org/10.1016/j.procir.2015.12.057.

Jetter, J., Eimecke, J. and Rese, A. (2018) "Augmented reality tools for industrial applications: What are potential key performance indicators and who benefits?", *Computers in Human Behavior*, vol. 87, pp. 18–33, [online] https://doi.org/10.1016/j.chb.2018.04.054.

Khuong, B. M., Kiyokawa, K., Miller, A., La Viola, J. J., Mashita, T. and Takemura, H. (2014) "The effectiveness of an AR-based context-aware assembly support system in object assembly", 2014 *IEEE Virtual Reality (VR)*. Minneapolis, USA, 29.03.2014 - 02.04.2014, pp. 57–62, [online] https://doi.org/10.1109/VR.2014.6802051.

Lv, Z., Lloret, J. and Song, H. (2022) "5G for mobile augmented reality", *International Journal of Communication Systems*, vol. 35, no. 5, [online] https://doi.org/10.1002/dac.5107.

Mattsson, S., Li, D. and Fasth, Fast-Berglund, Åsa (2018) "Application of design principles for assembly instructions – evaluation of practitioner use", *Procedia CIRP*, vol. 76, pp. 42–47, [online] https://doi.org/10.1016/j.procir.2018.02.011.

Milgram, P. and Kishino, F. (1994) "A Taxonomy of Mixed Reality Visual Displays", *IEICE Trans. Information Systems*, vol. E77-D, no. 12, pp. 1321–1329.
Neumann, U. and Majoros, A. (1998) "Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance", *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*, pp. 4–11, [online] https://doi.org/10.1109/VRAIS.1998.658416.
Orlosky, J., Kiyokawa, K. and Takemura, H. (2017) "Virtual and Augmented Reality on the 5G Highway", *Journal of Information Processing*, vol. 25, pp. 133–141, [online] https://doi.org/10.2197/ipsjjip.25.133.
Porcelli, I., Rapaccini, M., Espíndola, D. and Pereira, C. (2013) "Technical and Organizational Issues about the Introduction of Augmented Reality in Maintenance and Technical Assistance Services", *IFAC Proceedings Volumes*, vol. 46, no. 7, pp. 257–262, [online] https://doi.org/10.3182/20130522-3-BR-4036.00024.
Quint, F. and Loch, F. (2015) "Using Smart Glasses to Document Maintenance Processes", *Mensch und Computer* 2015, Stuttgart, Germany, vol. 95, pp. 203–208, [online] https://doi.org/10.1515/9783110443905-030.
Radkowski, R. (2015) "Investigation of Visual Features for Augmented Reality Assembly Assistance", *International Conference on Virtual, Augmented and Mixed Reality*, vol. 9179, pp. 488–498.
Rokhsaritalemi, S., Sadeghi-Niaraki, A. and Choi, S.-M. (2020) "A Review on Mixed Reality: Current Trends, Challenges and Prospects", *Applied Sciences*, vol. 10, p. 636, [online] https://doi.org/10.3390/app10020636.
Romero, D., T., Noran, O., Bernus, P., Berglund, Å. F. and Gorecky, D. (2016) "Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies", *International Conference on Computers & Industrial Engineering (CIE46), Tianjin, China, pp.1-11*.
Rosales, J., Deshpande, S. and Anand, S. (2021) "IIoT based Augmented Reality for Factory Data Collection and Visualization", *Procedia Manufacturing*, vol. 53, pp. 618–627, [online] https://doi.org/10.1016/j.promfg.2021.06.062.
Sarhan, Q. (2018) "Internet of Things: A Survey of Challenges and Issues", *International Journal of Internet of Things and Cyber-Assurance*, vol. 1, [online] https://doi.org/10.1504/IJITCA.2018.10011246.
Shiratuddin, M. F., Jamali, S. and Wong, K. (2014) "An Overview of mobile-Augmented Reality in Higher Education", *International Journal on Recent Trends In Engineering & Technology*, vol. 11, pp. 229–238.
Souza Cardoso, L. F. de, Queiroz Mariano, F. C. M. Q. and Zorzal, E. R. (2020) "A survey of industrial augmented reality", *Computers & Industrial Engineering*, vol. 139, p. 106159, [online] https://doi.org/10.1016/j.cie.2019.106159.
Szajna, A., Stryjski, R., Woźniak, W., Chamier-Gliszczyński, N. and Kostrzewski, M. (2020) "Assessment of Augmented Reality in Manual Wiring Production Process with Use of Mobile AR Glasses", *Sensors*, Basel, Switzerland, vol. 20, no. 17, [online] https://doi.org/10.3390/s20174755.
Um, J., Popper, J.; Ruskowski, M. (2018) "Modular augmented reality platform for smart operator in production environment", 2018 *IEEE Industrial Cyber-Physical Systems (ICPS)*, St. Petersburg.
Uva, A., Gattullo, M., Manghisi, V., Spagnulo, D., Cascella, G. L. and Fiorentino, M. (2018) "Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations", *The International Journal of Advanced Manufacturing Technology*, vol. 94, [online] https://doi.org/10.1007/s00170-017-0846-4.
van Krevelen, R. and Poelman, R. (2010) "A Survey of Augmented Reality Technologies, Applications and Limitations", *International Journal of Virtual Reality*, vol. 9, p. 1, [online] https://doi.org/10.20870/IJVR.2010.9.2.2767.
Wang, X., Ong, S. K. and Nee, A. Y. C. (2016) "A comprehensive survey of augmented reality assembly research", *Advances in Manufacturing*, vol. 4, no. 1, pp. 1–22, [online] https://doi.org/10.1007/s40436-015-0131-4.
Werrlich, S., Eichstetter, E., Nitsche, K. and Notni, G. (2017) "An Overview of Evaluations Using Augmented Reality for Assembly Training Tasks", *International Journal of Computer and Information Engineering*, vol. 11, no. 10, pp. 1129–1135, [online] https://doi.org/10.5281/zenodo.1132315.
Wilson, D.-M., Martin-Hammond, A. and Gilbert, J. (2012) "iTech: An Interactive Virtual Assistant for Technical Communication", *InTech*, [online] https://doi.org/10.5772/37455.
Xiao, L., Nouri, S., Hegland, J., Garcia, A. G. and Lanman, D. (2022) "NeuralPassthrough: Learned Real-Time View Synthesis for VR", *ACM SIGGRAPH Conference*, pp. 1-9, [online] https://doi.org/10.48550/arXiv.2207.02186.
Ziaee, O. and Hamedi, M. (2021) "Augmented reality applications in manufacturing and its future scope in Industry 4.0", *ArXiv, vol. abs/2112.11190*, [online] https://doi.org/10.48550/arxiv.2112.1119.
Zubizarreta, J., Aguinaga, I. and Amundarain, A. (2019) "A framework for augmented reality guidance in industry", *The International Journal of Advanced Manufacturing Technology*, vol. 102, no. 9, pp. 4095–4108, [online] https://doi.org/10.1007/s00170-019-03527-2.

https://doi.org/10.1017/pds.2023.86 Published online by Cambridge University Press