Potential and Limits of Augmented Reality in Engineering Education and Industry 4.0

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As a young class of socio-technical systems, Augmented Reality (AR), which enriches the real world with virtual information, is becoming increasingly important. It offers a variety of possibilities in the areas of education and training. Here, interactive and immersive learning experiences increase motivation and learning success. AR also enables the specific support of workers in the production environment. When dealing with complex tasks, AR applications help workers to increase efficiency and quality. Based on the developments of the BMBF collaborative project KORESIL, this paper contains an overview of the current application scenarios of AR in teaching and industry. The outlook provides an analysis of this technology's potential and identifies current challenges in hard- and software.

Keywords: Augmented Reality, Education 4.0, Industry 4.0, Mixed Reality, Socio-technical systems

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1 Introduction

Digital technologies are currently triggering a fundamental transformation that is affecting all areas of life. In terms of its impact, this process of digital transformation can be compared with the industrial revolution. In the professional sector in particular, the implementation of digital technologies and methods is associated with expectations especially with regard to increased work efficiency and quality. As a result, digitization is broadly expected to make a significant contribution to the competitiveness of companies [1, 2].

One sector of digital transformation with significant economic potential are socio-technical systems, which are characterized by a very intensive interaction between humans and machines. Such systems can be found in various areas such as healthcare, transportation, telecommunications, and, in particular, production. Socio-technical systems already show a significant influence on the way we work today. Their impact is further amplified by developments in modern production environments, as a result of which employees are less involved in the direct manufacturing process and instead perform complex monitoring and control tasks. In order to manage work with increasingly sophisticated technologies, digitally enhanced and easy-to-use socio-technical systems can provide essential support in both the learning and operating phase.

Such systems can be advantageously implemented in the form of Mixed Reality (MR) applications. These can be classified according to Milgram's Reality-Virtuality (RV) continuum, see Fig. 1. The concept relies on the two poles Real Environment and Virtual Environment. In between it spans a wide range of mixed reality, characterized by a seamless transition between Augmented Reality (AR) and Augmented Virtuality (AV) [3].

Especially AR is currently attracting great attention. Applications based on this technology have a broad application potential both for training and further education, as well as in the industrial processes of development and production. In AR, objects are superimposed on the user's field of view, thus enriching reality with supporting information from sensors, simulations or human experts in the back-office. In a similar way, new systems, technologies, and work processes can be made accessible in a playful and safe way. Here, the incorporation of 3D objects, sounds, and haptics enables an immersive training. The novel possibilities in teaching, training, industry or marketing associated with AR lead to the highest expected growth rate among all MR technologies [4, 5].

Common AR devices are holographic glasses, wrist devices such as smartwatches, tablets, info glasses, head-up displays or projector-based imaging devices. All of these

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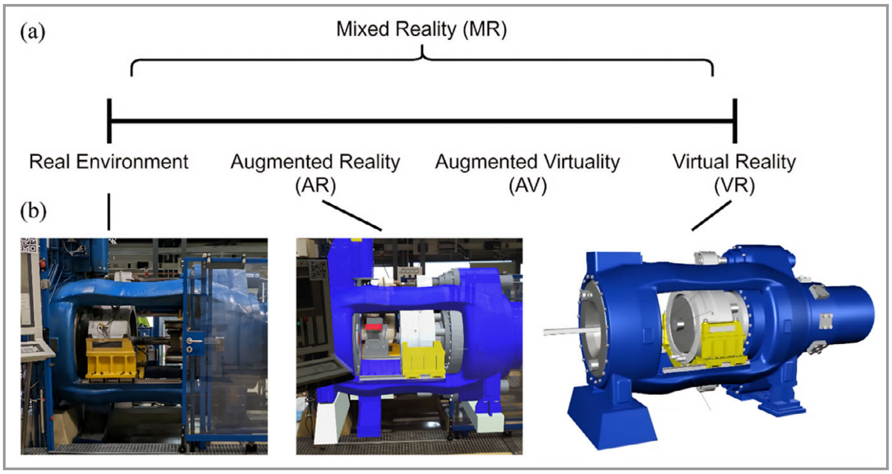

Figure 1. Milgram's Reality-Virtuality continuum (a) visualized using an extrusion press (b).

devices have undergone rapid development in recent years in terms of quality, functionality, costs, and availability. As a result, corresponding applications are already being used for training of employees on new equipment, risk-free practice of dangerous situations, or preparation of complex operations in medical technology [6–8]. Promising application scenarios are also available for university teaching in terms of learning environments enriched by simulations or remote labs [9, 10]. Here, it is particularly advantageous that the corresponding education and training applications can usually be employed independently of location and time. In component development, such solutions help to realistically visualize designs in civil and mechanical engineering and to jointly analyze them in globally distributed teams [11–13] (Fig. 2).

Concepts that provide employees with additional information directly during their work have particular potential for increasing the quality and efficiency of work, especially in the case of repetitive or complex tasks. Hence, it is possible to react quickly and purposefully to changing situations in industrial production and to increase process efficiency in this way [14, 15]. Likewise, installation, maintenance or quality assurance work [11, 16] as well as cooperation with robots [17] can be accompanied and supported. Some of these application scenarios are discussed in more detail in this paper with reference to the work in KORESIL.

The present impulse paper is part of a special issue of the journal *Chemie Ingenieur Technik*, which deals with challenges and opportunities in education in the context of Industry 4.0. The authors of this paper discuss various fields of application where AR technology is capable of improving training as well as production. The incorporated examples are based on the expertise available in the KORESIL research consortium, spanning both the technological and educational aspects of the respective institutes. Each field of application is compared with existing research in the field, while important aspects of development, implementation, and testing are discussed.

The intention is to showcase, what is currently possible with state-of-the-art AR technology combined with Industry 4.0 solutions. For instance, higher education or practical training can substantially benefit from enhanced immersive solutions. In industries such as the chemical industry, large facilities can be tested in the preface of installation and instructions or repair processes can be practiced without the need for physical presence on-site. With this impulse paper, the authors express their hope that readers find inspiration for their own field of expertise.

Figure 2. Merging the real and virtual worlds thanks to augmented reality. Potentials are given in numerous forms in the areas of industry as well as education.

2 Impulses from the KORESIL Project

The wide range of applications of MR was investigated by the KORESIL project on the basis of five example applications for a gesture- and voice-controlled AR device (holographic glasses, type: Microsoft HoloLens 2). The selection of the scenarios was based on the assessment of the research consortium, which includes five technical universities. The most important selection criterion was the

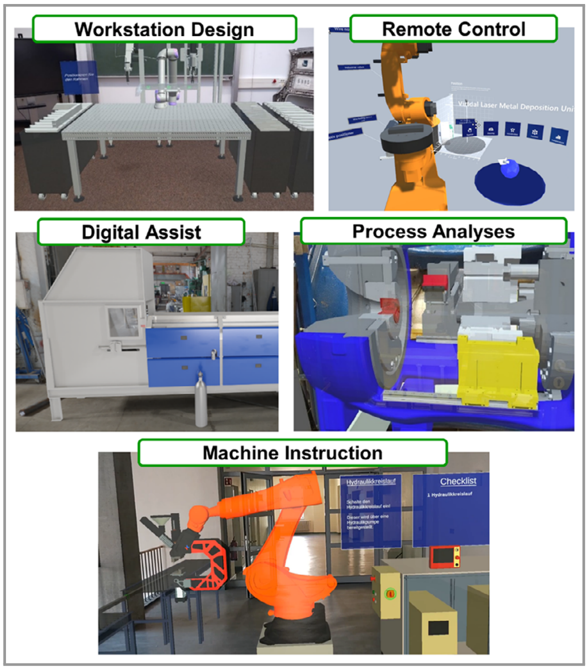

Figure 3. Overview of the AR applications of the joint project KORESIL. For each of the five examples the chapter highlights their main field of application regarding production and/or educational environments while addressing remaining technical challenges.

potential benefit for production companies. The application scenarios are shown in Fig. 3 and serve the following aspects:

– Supporting employees in the working environment
– Promoting in-depth plant and process understanding
– Monitoring and controlling production processes
– Minimizing downtime
– Improving technical marketing

Remote control has been at the center of AR developments in industrial applications in the recent years. While conventional remote control of machines is nothing new in the field of manufacturing [18] and education as well [9], AR offers a vastly more immersive user experience. Users can directly observe machines and processes in real time and in 3D. Until recently, remote control through AR mostly focused on immersive human-to-human collaboration where the actual remote control was performed by a person on-site, as the direct interface between machines and AR devices is not yet established [19]. Consequently, in the KORESIL project, the aspect of remote control was enhanced by directly linking the AR operator with the machine itself, circumventing the need for a person on-site. For example, the remote-controlled operation of a 3D printer and an industrial robot was realized with the aid of the aforementioned AR glasses. For this purpose, the communication interfaces of the machines were linked directly to the holographic glasses via a cloud-based approach. The user's actions are translated into data packets by the software, which are sent to a server via WiFi. There, they are processed and transmitted to the intended device, e.g., the robot. Due to the bilateral form of communication, sensor data can be sent to the AR glasses in return. These can be used, for example, to calculate and display 3D holographic images of the machines in real time. Such technologies thus enable humans to spatially separate from the operation and monitoring of machines.

Preliminary internal tests have shown that amongst experienced technicians as well as undergraduate students the applications are reported to be easy-to-use with a steep learning curve, once the general control of the AR device is mastered. However, in such applications, it can be problematic to integrate older production machines, as these often do not have the necessary modern interfaces. At the same time, the issue of data security must be addressed so that there is no externally controlled, possibly damaging intervention and no unwanted monitoring.

Even though the planning of entire factories or assembly processes is already performed digitally, the immersive experience is often realized through Virtual Reality (VR) [20]. AR by contrast can offer a better user experience, especially when working longer with a device [21]. Further, interactions with real objects and tools is naturally enabled, as the AR devices use transparent displays. This facilitates more in-depth planning of processes involving multiple tasks and tools.

In KORESIL, through an application for flexible *workstation design*, it was demonstrated that AR allows for a preparatory analysis of people and their actions in new work environments. Here, either different scenarios can be specified and compared, or users are given additional design freedom. This enables an optimized reconfiguration or redesign of workplaces without having to conduct cost-intensive tests in the real workplace. One possible scenario is the integration of cobots in an existing workplace. If the productivity of workers is to be increased, this can be done by automating simple work steps. However, since each person has individual needs and requirements for his or her workplace and also for enhancement by means of cobotics, these should first be tested and adapted to the individual. In an AR environment, the new cobot can be tested without the need to place it in different locations in the real workplace. In an adapted form, such a scenario can also be used for factory planning and larger reconstruction measures. The future human being operating in this environment should always be in the foreground of the planning. Currently, the integration of real components and tools into the AR environment is still challenging. Accordingly, results from pure AR analyses, in which the workers do not have to move any objects with mass, for example, are to be assessed critically.

In conjunction with the Industrial Internet of Things (IIoT), AR opens up new approaches for monitoring *process analysis*. Traditionally, the application of AR in such cases focused on the straightforward display of sensor data,

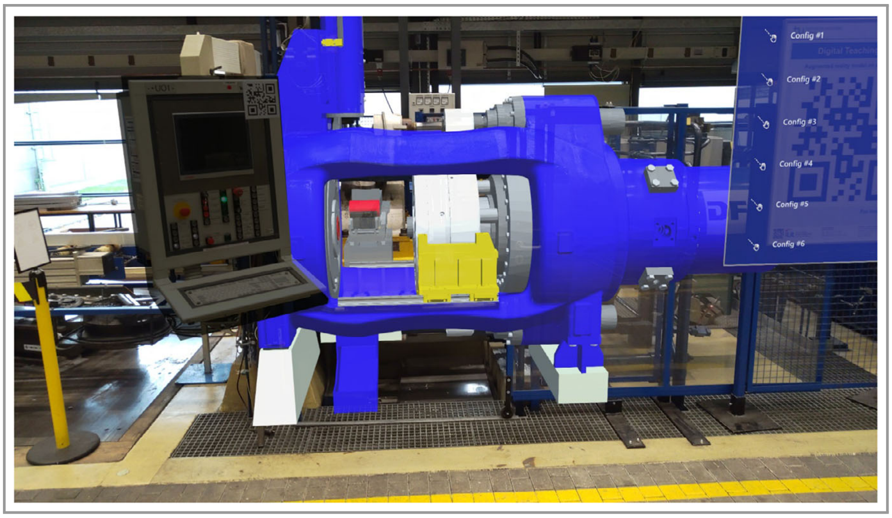

Figure 4. Detailed AR models of real production machines can be used for education and training purposes as well as directly in the production environment.

e.g., in the form of values or graphs when monitoring chemical processes [22]. To enhance the immersivity and allow for more complex decision making, the corresponding KORESIL application visualizes previously calculated computer simulation data holographically at the corresponding location in the machine [21].

Live sensor data serve as a basis for selecting which simulation to display. The comparison of current states (pressure, temperature, …) with previously calculated target states enables the user responsible for monitoring to intervene more quickly and in a more targeted manner and to better react to unforeseen situations. This is particularly true for states that lie outside the familiar monitoring ranges of automated systems, because human experience plays a greater role here. If sensor data is stored and remains linked to simulation data, training scenarios can be derived from this data. In training environments, specialists can then specifically try out how to react correctly to certain situations in a safe environment. At the same time, the real production plant does not have to be stopped or replicated for such training scenarios (Fig. 4).

A widespread field of application for AR in production environments is the category of *digital assist* [23]. Many companies have already gained experience with the concept of remote maintenance, in which an expert is connected to a local technician by means of an AR device. A video and audio stream can be transmitted so that communication can take place regardless of location. If holographic glasses are used, those working on site can continue to use their hands freely and at the same time receive relevant information, such as arrows, instructions, highlights, exploded drawings, etc., superimposed in the correct location. Through such systems, remote maintenance work can be carried out faster and more cost-effectively. The area of digital assist has been extended even further in the corresponding KORESIL application and additional scenarios have been added, such as the temporally asynchronous exchange of information (e.g., from one work-shift to the next). This allows important instructions or feedback to be digitally attached to a machine and retrieved at any time by an adequate device. Again, this does not necessarily have to be done on-site at the machine, but can also be performed at a digital twin. For corresponding applications to achieve added value in industry and training, they must be designed according to the requirements of the respective working environment and all those involved must be trained in their efficient operation.

In the context of Education 4.0, MR applications offer far-reaching potential [24]. MR technology itself, and herein especially holographic AR, is already an amalgamation of many, highly developed components in the fields of optics, sensor technology, software, and data processing. Thus, corresponding end devices represent a natural bridge between digital transformation in production and in education. As a classic application example for production-related training using AR, *machine instructions* were implemented in KORESIL using the example of an injection molding system. The users are guided through the start-up process of the system with cues and can check their success using a checklist. The repeated repetition of the work steps with successive reduction of the instructions is intended to consolidate the contents with the learners. The novelty of this application was the multimodal approach taken regarding the instructions.

Visual cues highlighting the relevant components are available together with text-based instructions as well as audio information for further guidance. In training applications of this kind, specialists can therefore try out the operation of systems and processes in a hazard-free training environment while individual learning preferences can be accounted for. At the same time, the actual production machine can continue to be used in operation. Corresponding scenarios must be designed in such a way that they authentically convey contexts and sustainably build up competencies. If such a training application merely replaces the direct instructions of a supervisor, the training promotes the rapid completion of tasks through visual support.

However, often learners do not go beyond the simple following of instructions and therefore lack a deeper understanding of their own actions. This superficial conduction of tasks potentially creates problems when applied to the real process or might hamper the improvement of processes by the users [25]. The former is especially problematic in the context of potentially dangerous situations, because the skilled workers do not recognize virtually non-visualized hazards later in reality if the tasks are completed as quickly as possible in the AR training environment. For this purpose, the KORESIL consortium has developed a novel collaboration technology, thanks to which, e.g., trainers and trainees can interact with each other time-synchronously and location-independently in the same AR environment. As known from other didactic contexts, an accompanying social component, and hence the new collaborative AR feature, promotes learning success and increases efficiency as well as safety.

3 Looking Ahead

MR applications have not yet reached the mainstream, either in manufacturing or education. This emerging class of socio-technical systems has not yet had its iPhone moment, or as it would recently be referenced, its chatGPT moment. These moments are characterized by their historical impact on the dissemination of a new technology. Even before the iPhone or chatGPT appeared, there were representatives of these technology classes, but with less widespread impact. What both cases have in common, however, is that they acted as catalysts for their respective industry or technology. From that point onward, the development and proliferation of associated technologies increased exponentially. For MR, this moment is yet to come.

In addition, there are currently still far-reaching challenges. For example, there is a lack of compelling, end-user-friendly, and affordable hardware for MR, but especially AR, the largest growth market within these technologies. AR devices are often too heavy and ergonomically immature, or their performance significantly limits the achievable application quality. In AR, the small field of view and image sharpness often acts as a limiting factor. These disadvantages no longer exist in the VR sector today. However, such devices are considered unsuitable for use in production environments from the point of view of occupational safety, as the users are no longer able to perceive their surroundings if the external cameras or the display fail.

In addition to the hardware, significant hurdles also remain at the software level. Currently, the development of sophisticated applications for a wide range of devices is very time-consuming and cost-intensive. This is comparable to homepage development in the 1990s. What was once a skill with enormous technical requirements can nowadays be done by anyone in an automated way. This must also be achieved for MR applications in order to generate a large number of high-quality applications with broad availability. Such applications are also the key to increasing acceptance among users, especially the older working population, which is rich in experience but less digitized [26]. A variety of factors play a decisive role here: degree of immersion, perceived interactivity, trust, ergonomics and comfort, intuitiveness and usability, customizability, quality of information, availability, and many more. As aptly formulated by Brunkow et al: "A high degree of perceived simplicity and perceived usefulness results in a positive behavioral attitude on the part of the user, which subsequently leads to the actual use of the technology" (quote from [27]). These aspects can only be met by a fine-tuned interaction of software and hardware.

In the design of education- and training-focused applications, new criteria for interaction design and subject-specific didactic guidelines must also be taken into account. With a prior knowledge in the requirements of low-immersive remote laboratories [28], the KORESIL consortium aimed to derive guidelines for the use of AR in manufacturing and education [21]. This research is still ongoing and supported by psychology experts, who are looking at interaction design from a different perspective. Their insights can provide valuable hints for the development of user-friendly applications adapted to the respective working and learning environments. This is a basic prerequisite for the successful use of these technologies as part of both Industry 4.0 and Education 4.0.

If the aforementioned challenges can be successfully addressed in the coming years, this technology offers enormous potential. The technology is not far from Steven Spielberg's visions in the 20-year-old classic Minority Report of gesture-controlled manipulation of images, data, sketches, models, and videos on semi-transparent displays or overlays in hard hats. Another key is likely to be the improvement of input interpretation by AI models. If the computer can correctly interpret user inputs at all times, the perceived intuitiveness and immersiveness can be significantly increased. This refers in particular to multimodal interactions with the virtual or augmented environment, i.e., when, for example, gesture, eye, and voice control are combined. Haptic feedback devices, such as force-feedback gloves, will make an important contribution to enhancing immersivity in this context, which was already shown by the KORESIL consortium [29]. Currently, full-body feedback systems are also being designed so that even more immersive interactions with the holographic objects can be experienced [30].

As Einstein already noted, every advance has an inconspicuous beginning. In order for AR to help drive the overall social trends Industry 4.0 and Education 4.0 forward, the use of this technology must be embraced at all decision-making levels. Intensive communication and support of necessary changes by the management level as well as flexibility and willingness of employees to undergo further training are essential prerequisites for fully exploiting the possibilities of AR technology. At the same time, a clear added value for the company and society must be defined and communicated. This can be, for example, an increase in productivity, faster training of skilled workers, or securing retiring expert knowledge. The right technology must be carefully selected for the various scenarios, so that in the end there is a benefit for both people and the company.

4 Summary

To strengthen competitiveness and innovation, the topic of Industry 4.0 and Education 4.0 is now well-established among companies and educational institutions. MR, and in particular AR, which enriches the real world with supporting information, is currently crystallizing as a promising technology for promoting these developments. This technology offers great potential for digital transformation in various areas of life, including industry and education in particular. With suitable applications, learning can be improved and the efficiency as well as the quality of work steps can be increased. In this impulse paper, novel technical solutions were discussed for different application scenarios and their potential in educational and industrial environments was evaluated. Especially for novel features like bilateral communication between holographic glasses and industrial machines as well as location-independent collaboration in augmented worlds, the successful implementation by using current technologies was described.

Currently, challenges still exist in the areas of user-friendly software and affordable, high-performance hardware. At the same time, humans need to be trained in interacting with the hardware and software on the one hand, and their behavior needs to be researched on the other hand, in order to derive design guidelines for AR applications used in industry and education. If people are supported by well-designed AR applications, the authors are convinced that AR technology can bring about far-reaching positive changes in both professional and private life.

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Abbreviations

AR augmented reality
MR mixed reality
VR virtual reality

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