Study of Hardware and Software Resources for Mobile Applications of Immersive Technologies in Manufacturing

Jozef Husár[1](✉), Lucia Knapčíková[1], and Justyna Trojanowska[2]

[1] Faculty of Manufacturing Technologies With a Seat in Prešov, Department of Industrial Engineering and Informatics, Technical University of Košice, Bayerova 1, 080 01 Prešov, Slovak Republic
{jozef.husar,lucia.knapcikova}@tuke.sk

[2] Faculty of Mechanical Engineering, Department of Production Engineering, Poznan University of Technology, Piotrowo Street 3, 61-138 Poznan, Poland
justyna.trojanowska@put.poznan.pl

Abstract. Immersive technologies (IT) create different experiences by combining the physical world with digital or simulated reality. Virtual augmented and mixed reality are the main types of immersive technologies. Since the beginning of the millennium, VR, AR and MR technologies have experienced rapid growth with significant research publications in technology and science. However, the engineering community has only minimally implemented these technologies so far. One of the challenges mechanical engineers face in understanding and using extended reality (ER) combining VR, AR, MR is the lack of hardware and software requirements specification. This document provides a literature review on mobile applications of immersive technologies in engineering production. A historical overview of the concept of applications used in industry was gradually created. Subsequently, the hardware and software pro-resources used for XR in production are presented. The article is intended to find a good fit between XR hardware and software solutions based on professional and technical knowledge in engineering fields.

Keywords: Augmented reality · Automotive industry · Visualization · Personalization

1 Introduction

The term "Extended Reality (XR)" refers to the growing category of immersive technologies that encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). As the popularity of virtual experiences continues to rise, particularly in response to the pandemic, XR technologies are becoming increasingly accessible to a wider audience. Many progressive industrial enterprises are already testing immersive technologies in their operations. The reason is the significant potential of technology

J. L. Afonso et al. (Eds.): SESC 2022, LNICST 502, pp. 23–34, 2023.
https://doi.org/10.1007/978-3-031-33979-0_3

to help people do their jobs better and more efficiently. With the rapid development of simulation technologies, computer graphics and human-computer interaction technologies, VR, AR and MR will gain more application domains. The market involving these technologies has grown incredibly. VR, AR and MR are used in several industries and concepts, from the manufacturing industry to consumers. It is the manufacturing industry that offers added value in countless applications. XR technologies such as AR, MR, and VR bring new solutions to industrial production by creating a blended environment where virtual and real objects can interact. These immersive technologies enhance the interaction between people by integrating digital technology into physical space. AR, MR, and VR are utilized when replicating reality is difficult or costly. Each technology has its distinct characteristics, with VR offering a completely virtual experience, AR adding virtual elements to the real world, and MR allowing interaction with these virtual elements in real-world scenarios. In recent years, VR and AR have become more accessible to individual users, but MR is still primarily used by large companies. While VR and AR can be used on mobile devices, MR requires more computing power.

1.1 VR, AR, MR: Conceptions

The convergence of digital and physical elements characterizes VR, AR, and MR. These cutting-edge technologies revolutionize human-computer interaction by seamlessly blending the virtual and real realms, delivering unprecedented experiences. Due to society's increasing demand for innovation and the investments and efforts of technology and mass media companies, these three realities are becoming more integral parts of our daily lives. To distinguish between them, it is crucial to comprehend their underlying concepts.

Virtual Reality (VR)

Virtual Reality (VR) is a computer-generated, fully immersive experience that consists of either computer-created environments and objects or 360-degree videos. To be considered VR, a program must completely alter the user's surroundings, creating a simulated environment that the user can interact with and perceive through a combination of sensory information [1]. The goal of VR is to accurately display and manipulate spatial models and scenes, recreating part of the real world with its laws and movements in 3D space, all in real-time. VR uses computer graphics and computer science techniques to achieve this and provides content through a head-mounted display (HMD) or headset. The content is purely digital and the user is transported to a new 3D digital environment, separate from the real world [2].

Augmented Reality (AR)

"Augmented Reality" is a term that describes a technology that combines real-world and computer-generated content in real-time. It leverages the advancements made in Virtual Reality (VR) and enables interaction between the physical and virtual realms [3]. It is the projection or adding a layer of digital content to a real physical environment in real time. Augmented reality integrates digital components through applications on mobile devices into the real world, and digital content is visible through special AR glasses or using a tablet/smartphone, stationary screens, projection devices and other technologies [4]. AR, as defined by [5], is a technology that merges the real world with computer graphics and enables real-time interaction between objects. It has the capability to track objects, recognize objects and images, and provide real-time data and contextual information. Augmented reality has different types that fall into two categories. These include brand-based augmented reality, and brand-free augmented reality.

Mixed Reality (MR)

Mixed Reality (MR) is a technology that allows digital and real objects to interact and coexist in real-time. The user can manipulate digital objects, which then react as real, physical objects would. This technology is also known as hybrid reality and requires a more powerful MR headset and processing power compared to VR or AR. MR brings together various technologies into a single wearable device [6]. The objective of MR is to achieve a seamless fusion of the real and digital realms through the stimulation of the user's senses and incorporating digital information into their line of sight. The difficulty in MR technology lies in registering virtual and real content accurately in real-time and presenting computer-generated 3D graphics. Currently, efforts are focused on enhancing tracking capabilities, particularly for mobile devices.

1.2 VR, AR, MR: Development

The origin of immersive technologies dates back to 1838 when charles wheatstone invented the stereoscope [8]. This technology was used to create 3D images. Since then, these technologies have developed at a rapid pace but have remained a subject of interest until today. This chapter presents the appearance and development of VR, AR and MR.

VR Development

Virtual Reality (VR) as we know it has evolved over several decades due to advancements in technology and more affordable high-performance computing processors. Key milestones in VR's development include:

- Sensorama (1960–1962) by Morton Heilig, the first attempt at VR with a multisensory simulator that played pre-recorded films with 3D display, stereo sound, fans, scent generator, and vibrating chair.
- The Ultimate Display (1965) proposal by Ivan Sutherland, combining interactive graphics, force feedback, sound, smell, and taste.
- "Sword of Damocles" (1967) - the first VR system with hardware, believed to be the first head-tracking HMD.
- GROPE (1971) - a force-feedback system prototype at the University of North Carolina.
- VIDEOPLACE (1975) by Myron Krueger, an artificial reality system projecting users' silhouettes captured by cameras onto a large screen for interaction.
- VCASS (1982) - Thomas Furness developed an advanced flight simulator using an HMD to display targeting information and extend the view from the window.
- VIVED (1984) - NASA Ames built a Virtual Visual Environment Display using standard stereoscopic monochrome HMD technology.
- VPL - produced the first commercially available VR devices, the DataGlove (1985) and Eyephone HMD (1988).

- BOOM - a box with two CRT monitors viewed through eye holes, allowing users to move around in a virtual world with a mechanical arm tracking their position and orientation.
- UNC Walkthrough Project (1980s) - an architectural walkthrough application at the University of North Carolina using HMDs, optical trackers, and Pixel-Plane graphics engine to enhance VR experience.
- Virtual Wind Tunnel (early 1990s) - developed at NASA Ames, this system allowed for flow field study using BOOM and DataGlove.
- CAVE (1992) - a high-quality visualization system that projects stereoscopic images onto a room's walls, providing better resolution and wider field of view than HMD-based systems.

Prior to the emergence of commercial high-end VR systems, such as the Samsung Oculus Rift and HTC Vive, in the early 2010s, VR technology was limited to specialized researchers and came with a hefty price tag, hindering its commercial viability [10, 11]. While these commercial VR systems are connected to high-end PCs, providing users with high refresh rates, immersive environments, and multiple interaction options, they are confined to a limited space near the PC and require significant computing power, which can be expensive [12]. A more budget-friendly VR option is VR-compatible mobile devices (smartphones), which may not offer the same quality VR experience as the high-end systems but are more affordable due to their lower computing power [13].

AR Development

In the early 1990s, augmented reality gained significant attention and became the subject of numerous research projects due to its immense potential. The history of Augmented Reality (AR) includes the following milestones:

- 1990 - Tom Caudell was the first to use the term "Augmented Reality".
- Virtual Fixtures (1992) - An early AR system developed by Louis Rosenburg for the USAF Armstrong Research Laboratory, allowing military personnel to control machines.
- Dancing in Cyberspace (1994) - A theatrical production with acrobats dancing with virtual objects projected on stage.
- NASA X-38 spacecraft (1999) - Used a hybrid synthetic vision system with AR technology for navigation.
- ARToolKit (2000) - Open source software library for AR development.
- 1st & Ten (2003) - Improved graphics system for sports with overlaid graphics.
- Esquire magazine (2009) - Used AR in print media for the first time.
- Volkswagen's MARTA (2013) - AR app for technicians with detailed instructions.
- Google Glass (2014) - AR glasses connecting to internet via smartphone Bluetooth.
- Microsoft's HoloLens (n.d.) - Advanced AR headset running on Windows 10.
- IKEA Place (2017) - AR app for virtual tryout of home decor before purchase.
- ARKit (2017) - Added to iOS 11 by Apple for quick AR app creation.

MR Development

In their 1994 paper "A Taxonomy of Mixed Reality Visual Displays," researchers Paul Milgram and Fumio Kishino introduced the concept of MR. They described a "virtuality continuum" that connects the real and virtual worlds. Originally, Milgram and Kishino envisioned MR mainly in terms of visual displays, but it has since expanded to encompass information perceived by other senses as well [14]. MR is a combination of VR and AR technology. It gained popularity after the introduction of Microsoft HoloLens. However, it's still hard to find many options that offer a true "MR" experience. Among vendors experimenting with mixed reality, information about how the technology works is scarce. In 2018, Magic Leap announced the launch of its first mixed reality glasses, the Magic Leap One Creator Edition. The kit was sold in six US cities and cost $2,295[15]. In 2021, Magic Leap introduced the second version of its headset. Unlike VR, Magic Leap's AR headsets project digital 3D objects on top of the real world. The new headset is primarily intended for corporate use and has a wider field of vision [16].

2 Research

Today, XR technologies have gained great popularity and many application domains. One of the most important areas of their use is education. For example, Google Expeditions interactive technology allows students to sit in their classroom and immerse themselves in virtual worlds. Similarly, applications such as Unimersiv fully engage students in a virtual environment where they can even hear sounds, such as people speaking foreign languages, etc., which has been proven to help with learning and development. 9 out of 10 UK teachers acknowledge that XR technologies would benefit their teaching [16] (Fig. 1).

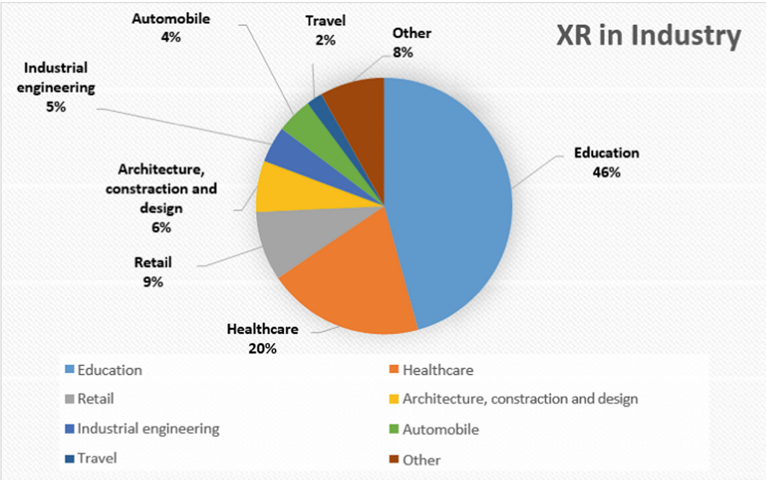

Fig. 1. XR in Industry [16]

Aside from education, XR technologies are also applied in fields such as design, architecture, and engineering. Virtual reality has many potential uses, one of which is allowing architects to create 1:1 scale models of their projects, which they can then examine, manipulate, and test before actual construction begins. Automotive engineers can also use VR to design and develop new cars and engines, saving costs by avoiding the creation of multiple physical prototypes. Furniture manufacturers are now utilizing AR technology to let customers virtually try out furniture in their homes prior to purchasing. XR provides an innovative way for people to immerse themselves in various new scenarios through simulation technology, and offers practical solutions to contemporary challenges.

Examples of XR Applications in Manufacturing:

In the field of manufacturing, XR has shown potential for enhancing maintenance processes. A case study was conducted in a Swedish snus company to explore the benefits of a wearable AR system for maintenance tasks. The study involved developing an AR system for a toolbox and testing it with 17 experts at a maintenance fair in Sweden. The results of the study indicated that AR can support maintenance in manufacturing. However, designing AR interfaces requires more attention, as they are different from traditional 2D interfaces. It is crucial to have a good understanding of the production activity and available AR technologies before implementing an AR system to ensure optimal results [17].

An XR application was demonstrated at a drone factory in Sweden's National Test Laboratory. The factory relied mainly on traditional operator support like paper instructions and monitor-based illustrations [18]. The study explored the new possibilities of using an AR system to present instructions, including structural and active diagram-based instructions, and incorporating tablets and Microsoft HoloLens. The AR mounting support system was tested with two control methods: touchscreen buttons and voice commands. The results showed that assembly operations using functional diagram-based instructions were faster and more accurate than those using the structural diagram approach. The operators using tablets performed better on average than those using HoloLens [19].

An AR impact study was conducted at a Swedish firm specializing in indoor climate and ventilation solutions. The study aimed to examine the effects of AR on order picking using a HoloLens device and Unity3D software. Five company representatives tested the AR system on two orders, each with 12 or 14 items. Despite all participants correctly selecting the items, the average selection time was longer than expected due to user habits, AR limitations, and device limitations. The results showed the potential for AR to enhance order picking, despite the challenges posed by new wearable technology [20].

In another study at a Swedish global automotive company's R&D center, the impact of VR was evaluated on two virtual production activities: spot welding operator training and product design review. The study used two interaction approaches: BHI (hand tracking) and CBI (controller-based interaction) in the VR system. 22 engineers tested and evaluated the system and data was collected on immersion, interaction, and autonomy to compare the effects on the user experience. Results showed that hand tracking and synchronized visualization received higher preferences as they provided a more realistic experience and increased immersion. However, hand interaction with virtual objects proved to be more difficult than controller-based interaction. The study highlighted that XR technology brings new solutions and potential improvements but also new challenges that may hinder its widespread adoption in the industry [21].

3 HW and SW Tools for XR Application in the Manufacturing

3.1 HW Tool for VR, AR, MR Applications

Through the years, XR technology has advanced, leading to the development of increasingly sophisticated devices that are also smaller and more user-friendly. The devices differ in terms of appearance, weight, operating mode, field of view (FOV), and frames per second (FPS) capabilities [22].

For any XR system, a display screen is required to project virtual content. The FOV of the screen determines the visible area for the user, affecting the amount of virtual information that can be displayed. Ideally, the screen used in XR technologies should have a similar FOV as human eyes (114° horizontally) [23] to provide a more immersive experience and display important information effectively. However, currently available screens have varying FOVs, with VR headsets offering a wider FOV ranging from 90° to 110° (e.g. HP Reverb (G1), Oculus Quest, HTC Vive Cosmos) and some advanced models offering up to 200° (e.g. Pimax Vision 8K X).

Another important parameter is the FPS, which is the frequency of displaying successive images on the screen [23]. Higher FPS results in smoother content movement. Although FPS is important in AR or MR systems, it is more critical in VR systems, where users are fully immersed in a computer-generated environment. A recommended FPS for VR systems is 90 fps to avoid motion jitter and motion sickness, while AR or MR systems require 30–60 fps. Note that FPS is determined by both hardware and software.

The following listed HW tools for XR application in the manufacturing industry are the most promising and are most commonly used [21]:

HTC Vive

The HTC Vive is a VR headset created by HTC in collaboration with Valve, a video game developer. It boasts a high-res display of 2160 x 1200 with a refresh rate of 90Hz and a 110-degree FOV [26].Despite its advanced technology, the Vive is lightweight, weighing just over half a kilogram. It requires a powerful computer to run, with over 70 sensors such as a gyroscope, accelerometer, and laser position sensors providing a room-scale experience. The Vive also has a pro version that features improved resolution of 2880 x 1600 and wireless capabilities [24].

Oculus Rift

The original version of the headset was introduced in 2016 and had many similarities with the Vive, including its resolution and refresh rate, but lacked hand controls and room-scale capabilities. The Oculus Touch, a handheld controller system, was later released to provide a room-scale alternative to the Vive [27]. The Oculus Touch kit includes a headset and the controller. It also requires a relatively powerful computer, similar to the HTC Vive.

Microsoft Hololens

The Microsoft Hololens, noted as the preferred option for AR/MR in manufacturing, boasts a 2–3 h battery life and operates as a standalone device, eliminating the need for a computer connection. Its 3D content is created by two light sensors and holographic lenses, producing a total resolution of 2.3 million light points. The device is equipped with an Inertial Measurement Unit, four cameras for environmental processing, an RGB camera, and a depth camera for mapping and merging the real and virtual worlds. Other features include four microphones, eye-tracking, gesture input, surround sound, and voice support [29].

Mobile Headset

Contrarily to the dedicated XR hardware mentioned earlier, devices like Samsung Gear VR, Google Daydream, and Google Cardboard are not standalone XR devices. These are plastic or cardboard head-mounted displays that depend on the display of a mobile phone. The major difference between these mobile XR solutions lies in their compatibility, ergonomics, and build quality. They are generally more affordable and portable, only needing a mobile phone instead of a computer. However, their tracking capabilities are limited due to the use of the phone's internal sensors and gyroscopes instead of advanced tracking hardware found in high-end headsets like the Oculus Rift and HTC Vive [31]. Another disadvantage is the low frame rate, with a recommended 90 Hz for a smooth user experience [32], which is difficult to achieve with a mobile phone. Mobile AR has the potential to improve project documentation comprehension and usability through visualizing preliminary studies and monitoring the manufacturing process [33]. However, it also has limitations such as poor alignment with the surrounding environment and a lack of a motion controller in some cases [34, 35]. Specialized AR devices such as the Microsoft Hololens are preferred in the construction phase due to these limitations.

3.2 SW Tools for VR, AR, and MR Applications

In production, various software are used to develop XR systems, either based on open-source platforms or commercial software. Open-source platforms offer more customization but require programming skills, while commercial software is user-friendly and easy to use with pre-existing XR features. However, the ability to try out new XR features is limited, as it depends on the software's updates [21].

Open development platforms

Unity3D [36] and Unreal Engine [37] are two of the most widely used open platforms that support XR technologies. These platforms have large and active communities that have developed fast-changing plugins that the manufacturing industry can quickly implement for custom XR development. Unity3D has gained recognition in the production industry through partnerships with top manufacturers globally, while Unreal Engine is well-known for its ability to produce photorealistic visualizations with ease.

Commercial SW platforms

The popularity of XR technology has led to its incorporation into commercial software used in manufacturing. XR experiences can be created using either open development platforms or commercial software. Open platforms offer customization but require software engineering skills, while commercial software is user-friendly but limited in exploring new XR features [38]. In the manufacturing industry, Siemens Plant Simulation supports VR for assembly line design analysis and maintenance training for steam turbines [39]. Autodesk VRED is used for creating 3D product visualizations, virtual prototypes and VR, mainly in the automotive industry [40]. The latest version of ABB Robot Studio has improved its VR capabilities for better robotic system workspace [41]. Vuforia Studio enables rapid AR app development for operator support and training [42, 43]. Revizto is a software solution for real-time collaboration and coordination issues in AEC projects, with a focus on BIM [44]. It enables all project teams to work together on a single model, ensuring accurate and efficient collaboration. Revizto converts BIM and CAD models from popular tools like Trimble SketchUp, Autodesk Revit, and Autodesk AutoCAD into VR environments that can be navigated with Oculus and HTC Vive [45].

Atensi offers game-based learning solutions through interactive simulations of real-world scenarios, particularly in training and risk task simulations in the construction industry [46]. Dimension10, like Revizto, focuses on seamless BIM to VR and cloud storage. It supports popular BIM software from Autodesk and Solidworks, allowing multiple participants to collaborate in a scalable virtual space [47].

Trimble SiteVision is different from the other software mentioned in that it offers an AR experience instead of VR. With this software, users can visualize a construction site in the future or view what's underground, using Trimble's GNSS (Global Navigation Satellite System) hardware, which is connected to the user's phone or tablet [48]. Unlike the other software, which prioritize functionality over design, Trimble SiteVision provides an AR experience that enables users to see real-life construction sites.

4 Conclusion

As the manufacturing industry transforms digitally, XR technology is seen as the cornerstone for Industry 4.0. XR, in its forms of AR, MR, and VR, has transformed the interaction between users and computer systems. Initially, XR systems were limited by hardware and software constraints, making them costly and purpose-built. However, with technological advancements, XR systems are now more affordable and flexible, becoming as accessible as mainstream computer hardware. Different levels of virtuality offer pros and cons for specific tasks. For example, VR systems provide an immersive virtual environment but require more complex modeling, while AR systems can display additional information easily, but may face challenges with object tracking. Even within the same level of virtuality, there are varying hardware and software specifications. Wireless VR solutions offer mobility but have lower computing power and shorter operating times. Choosing the right XR solution for manufacturing activities requires expertise as XR devices vary in appearance and technical characteristics, such as weight, operating mode, field of view, and frames per second. Finding a match between XR and manufacturing requires a deep understanding of both. Today's XR headsets have a wide FOV - about 90–110 degrees, and some advanced models even have a FOV of 200 degrees. While for AR or MR systems, an FPS of 30–60 frames/s would be sufficient, for VR systems, an FPS of 90 frames/s is recommended. In the manufacturing industry, the most used hardware is HTC Vive, Oculus Rift, Microsoft Hololens and mobile headsets, but they have their disadvantages related to the performance of mobile devices. As for the software for XR, usually, this software is based on an open development platform, such as Unity3D and Unreal Engine, or is commercial, such as Plant Simulation, Autodesk

VRED, ABB Robot Studio, Vuforia Studio, Revizto, Atensi, Dimension10, Trimble SiteVision. Of course, the choice of hardware and software depends on the area and purpose of the XR implementation.

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

Article is the result of the Project implementation: Development of excellent research capacities in the field of additive technologies for the Industry of the 21st century, ITMS: 313011BWN5, supported by the Operational Program Integrated Infrastructure funded by the ERDF.

References

1. Gatial, P.: Virtual reality. http://edu.fmph.uniba.sk/~winczer/SocialneAspekty/GatialVirtualnaRealita.htm. Accessed 03 Nov 2022
2. The ultimate VR, AR, MR guide. https://www.aniwaa.com/guide/vr-ar/ultimate-vr-ar-mr-guide/. Accessed 03 Nov 2022
3. Wirth, W., Hartmann, T., Böcking, S., et al.: A process model of the formation of spatial presence experiences. Media Psychol. **9**, 493–525 (2007). https://doi.org/10.1080/15213260701283079
4. Grubert, J., Langlotz, T., Zollmann S., et al.: Towards pervasive augmented reality: context-awareness in augmented reality. In: IEEE Transactions on Visualization and Computer Graphics, vol. 23, no. 6, pp. 1706–1724 (2017). https://doi.org/10.1109/TVCG.2016.2543720
5. Blimber, O.: Spatial augmented reality: merging real and virtual worlds. A K Peters, Wellesley (2005)
6. Mazuryk, T., Gervautz, M.: Virtual Reality—History, Applications, Technology and Future. TU Wien University, Vienna, Austia (1996)
7. Milgram, P., Takemura, H., Utsumi, A., Kishino, F.: Augmented reality: a class of displays on the reality-virtuality continuum. In: Das, H. (ed.) Telemanipulator and Telepresence Technologies, pp. 282–292 (1995). https://doi.org/10.1117/12.197321
8. Forrest, C.: Infographic: the history of AR and VR, and what the future holds. https://www.techrepublic.com/article/infographic-the-history-of-ar-and-vr-and-what-the-future-holds/. Accessed 04 Nov 2022
9. Poetker, B., (2019). A brief history of augmented reality. https://www.g2.com/articles/history-of-augmented-reality. Accessed 04 Nov 2022
10. Zinchenko, Y., Khoroshikh, P., Sergievich, A., et al.: Virtual reality is more efficient in learning human heart anatomy especially for subjects with low baseline knowledge. In: New Ideas in Psychology, vol. 59, no. 100786 (2020). https://doi.org/10.1016/j.newideapsych.2020.100786
11. Carruth, D.: Virtual reality for education and workforce training. In: Proceedings of the 15th International Conference on Emerging eLearning Technologies and Applications (ICETA), Stary Smokovec, Slovakia, 26–27 October (2017). https://doi.org/10.1109/ICETA.2017.8102472
12. Radianti, J., Majchrzak, T., Fromm, J., et al.: A systematic review of immersive virtual reality applications for higher education: design elements, lessons learned, and research agenda. In: Computer Education, vol. 147, no. 103778 (2020). https://doi.org/10.1016/j.compedu.2019.103778
13. Mazuryk, T., Gervautz, M.: Virtual reality history, applications, technology and future. Institute of Computer Graphics Vienna University of Technology, Austria. p. 72. (1999)

14. Milgram, P., Kishino F.: A taxonomy of mixed reality visual displays. In: IEICE Transactions on Information Systems, Vol E77-D, no. 12, pp.1321–1329 (1994)
15. Kretsu, C.: Timeline: how virtual, augmented and mixed reality evolved. https://vc.ru/future/44433-hronologiya-kak-razvivalas-virtualnaya-dopolnennaya-i-smeshannaya-realosti. Accessed 02 Nov 2022
16. What Is the future of XR?. https://www.hire-intelligence.co.uk/the-future-of-xr/. Accessed 02 Nov 2022
17. Kraft, H., Mäki, H., Bengtsson, J., et al.: Augmented reality in preventive maintenance. Bachelor thesis, Dept. Ind. Mater. Sci., Chalmers Univ. Technol., Gothenburg, Sweden, (2018). https://hdl.handle.net/20.500.12380/255323. Accessed 04 Nov 2022
18. Hansson, O., Nadum, O.: Model based operator instructions using AR-technology, M.S. thesis, Department of Industrial and Materials Science Chalmers University of Technology Gothenburg, Sweden (2019). https://hdl.handle.net/20.500.12380/300753. Accessed 04 Nov 2022
19. Agrawala, M., Phan, D., Heiser, J., Haymaker, J., et al: Designing effective step-by-step assembly instructions. ACM Trans. Graph. **22**(3), 828–837 (2003). https://doi.org/10.1145/882262.882352
20. Mahmutovic, A., Andreasson, A., Söderström, L.: Effektivisering av plockprocessen i lager med hjälp AV AR, Bachelor thesis, Department of Industrial and Materials Science Chalmers University of Technology Gothenburg, Sweden (2018). https://hdl.handle.net/20.500.12380/255328. Accessed 03 Nov 2022
21. Gong, L., Fast-Berglund, A., Johansson, B.: A framework for extended reality system development in manufacturing. IEEE Access **9**(1) , 24796–24813 (2021). https://doi.org/10.1109/ACCESS.2021.3056752
22. Gong, L.: Developing extended reality systems for the manufacturing industry. Thesis for the Degree of Doctor of Philosophy, Department of Industrial and Materials Science Chalmers University of Technology Gothenburg, Sweden (2020)
23. Howard I., Rogers, B.: Binocular vision and stereopsis. New York, NY, USA: Oxford University Press (1996). https://doi.org/10.1093/acprof:oso/9780195084764.001.0001
24. Kaushal, V.: Exploratory study: implementation and applications of extended reality. Master's Thesis, Faculty of Science and Technology, University of Stavanger, Department of Mechanical and Structural Engineering and Materials Science (2019)
25. Martindale, J.: Oculus Rift vs. HTC Vive. https://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/. Accessed 04 Nov 2022
26. Jaffrey Van Camp: Review: HTC Vive Pro. https://www.wired.com/review/review-htc-vive-pro/. Accessed 04 Nov 2022
27. Lang, B.: Oculus Rift and HTC Vive Roomscale Dimensions Compared. https://www.roadtovr.com/oculus-touch-and-htc-vive-roomscale-dimensions-compared-versus-vs-visualized/. Accessed 04 Nov 2022
28. Burns, Ch.: Oculus Rift just cut price for 3rd time this year. https://www.slashgear.com/oculus-rift-just-cut-price-for-3rd-time-this-year-11503613/. Accessed 03 Nov 2022
29. Evans, G., Miller, J., Pena, M.I., MacAllister, A., et al.: Evaluating the Microsoft Hololens through an Augmented Reality assembly application. Degraded Environ.: Sens., Process., Display **10197**, 101970V (2017). https://doi.org/10.1117/12.2262626
30. Manufacturers are successfully using mixed reality today. https://www.themanufacturer.com/articles/manufacturers-are-successfully-using-mixed-reality-today/. Accessed 04 Nov 2022
31. Painter, L.: Daydream VR vs HTC Vive & Oculus Rift | Mobile VR vs PC VR. https://www.techadvisor.com/review/daydream-vr-vs-htc-vive-oculus-rift-mobile-vr-vs-pc-vr-3647738/. Accessed 03 Nov 2022

32. Schlueter, J., Baiotto, H., Hoover, M., et al.: Best practices for cross-platform virtual reality development. Degraded Environ.: Sensing, Process. Display **10197**, 1019709 (2017). https://doi.org/10.1117/12.2262718
33. Meža, S., Turk, Z., Dolenc, M.: Measuring the potential of augmented reality in civil engineering. Adv. Eng. Softw. **90**, 1–10 (2015). https://doi.org/10.1016/j.advengsoft.2015.06.005
34. Heinzel, A., Azhar, S., Nadeem, A.: Uses of augmented reality technology during construction phase. In: 9th International Conference of Construction in the Twenty-first Century (CITC9), 5. – 7. marca 2017, Dubaj (2017)
35. Kaščak, J., Husár, J., Knapčíková, L., Trojanowska, J., Ivanov, V.: Conceptual use of augmented reality in the maintenance of manufacturing facilities. In: Trojanowska, J., Kujawińska, A., Machado, J., Pavlenko, I. (eds.) MANUFACTURING 2022. LNME, pp. 241–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-99310-8_19
36. Unity. https://unity.com/. Accessed 04 Nov 2022
37. Unreal Engine, https://www.unrealengine.com/. Accessed 04 Nov 2022
38. Syberfeldt, A., Danielsson, O., Gustavsson, P.: Augmented reality smart glasses in the smart factory: product evaluation guidelines and review of available products. IEEE Access **5**, 9118–9130 (2017). https://doi.org/10.1109/ACCESS.2017.2703952
39. Zhou, Y., Liu, W.: Design of virtual overhaul system for condensing steam turbine based on Unity3D. In: Proceedings of the 12th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), 28– 29. február, Phuket, pp. 204–207 (2020)
40. Stylidis, K. Dagman, A., Almius, H., et al.: Perceived quality evaluation with the use of extended reality. In: Proceedings of the Design Society: International Conference on Engineering Design, 5.– 8. august, Delft, vol. 1, no. 1, pp. 1993–2002 (2019)
41. Holubek, R., Delgado Sobrino, D. R., Koštál, P., et al.: Offline programming of an ABB robot using imported CAD models in the robotstudio software environment. Appl. Mech. Mater. **693**, 62–67 (2014). https://doi.org/10.4028/www.scientific.net/AMM.693.62
42. Luo, X., Mojica Cabico, C.D.: Development and evaluation of an augmented reality learning tool for construction engineering education. In: Proceedings of the Construction Research Congress 2018: Construction Information Technology, 2. – 4. april, New Orleans, pp. 149–159 (2018). https://doi.org/10.1061/9780784481301.015
43. Kascak, J., Teliskova, M., Torok, J., et al.: Implementation of augmented reality into the training and educational process in order to support spatial perception in technical documentation. In: Proceeding of the IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA), 26. – 29. april, Tokio, pp. 583–587, (2019). https://doi.org/10.1109/IEA.2019.8715120
44. Next level BIM coordination, Revizto. https://revizto.com/en/. Accessed 04 Nov 2022
45. Lau, W.: Revizto quickly turns building models into virtual reality experiences. https://www.architectmagazine.com/technology/revizto-quickly-turns-buildingmodels-into-virtual-reality-experiences. Accessed 03 Nov 2022
46. Varonis, E.M., Varonis, M.E.: Deconstructing candy crush: what instructional design can learn from game design. Int. J. Inf. Learn. Technol. **32**(3), 150–164 (2015). https://doi.org/10.1108/IJILT-09-2014-0019
47. Dimension10. https://dimension10.com/. Accessed 03 Nov 2022
48. What is Trimble SiteVision, Trimble SiteVision. https://sitevision.trimble.com/. Accessed 02 Nov 2022