Handbook of Manufacturing Systems and Design

An Industry 4.0 Perspective

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First edition published 2024

ISBN: 978-1-032-35321-0 (hbk)
ISBN: 978-1-003-32752-3 (ebk)

8 Mixed Reality for Industry 4.0 in Manufacturing Systems

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DOI: 10.1201/9781003327523-10

The funder for this chapter is University of Luxembourg.

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

8 Mixed Reality for Industry 4.0 in Manufacturing Systems

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8.1 INTRODUCTION

Human interactions still play a significant role despite the advancements in the manufacturing landscape with Industry 4.0 technologies. Moreover, the aim of Industry 4.0 is not to replace machines with humans but to enhance human capability with the support of advanced technologies. The market trends suggest an increased demand for customized products, increasing the product variants and hence more demand on the shopfloor (Kolla et al., 2020). Therefore, operators need systems that can assist them in completing their tasks quicker, more precisely, and with a lesser workload. Extended reality (XR) technologies can be employed in the industry to give operators an enhanced perception of the instructions in a visual and interactive manner (Doolani et al., 2020; Fast-Berglund et al., 2018). The XR spectrum includes technologies such as augmented reality (AR), mixed reality (MR), and virtual reality (VR). Figure 8.1 illustrates the XR spectrum, which encompasses AR, MR, and VR technologies.

The virtual extreme of the XR continuum is VR. In VR, the user is completely immersed in the virtual world and isolated from the real environment (Mujber et al., 2004). In a VR environment, the user is surrounded by virtual objects and is unaware of reality. On the other hand, the real world is the other extreme, consisting exclusively of physical objects and free of any virtual objects to improve the operator's perception. AR and MR enhance the user experience by improving reality with virtual elements. In an AR environment, the virtual information is overlaid in the natural environment. However, in an MR environment, it is possible to develop interactions between real and virtual objects. Therefore, MR can be considered an umbrella term for AR and VR. In a nutshell, AR and MR can be differentiated based on the extent of interactions between real and virtual elements.

Numerous advantages of XR technology include traceability, increased intuitive learning, decreased error rates, and reliability. AR and MR can help shop floor employees in their daily jobs by enabling digital poka-yoke systems and reducing

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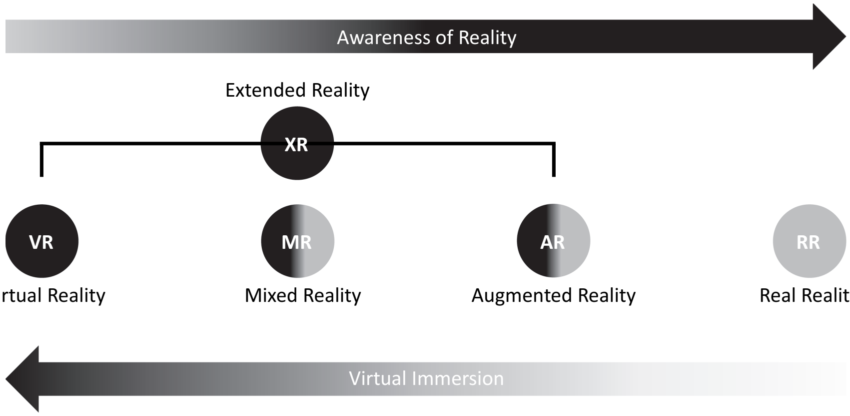

FIGURE 8.1 Extended reality (XR) spectrum illustrating both virtual and real extremes of awareness.

manual errors and rework of complex and unfamiliar assembly tasks. VR can be effectively employed in training activities in any manufacturing enterprise. A new way of interacting with machines and the shop floor environment is also introduced by XR, opening the door for future solutions for human-machine interfaces (HMI).

This chapter is structured as follows: Section 8.2 presents basic components and different types of AR systems, followed by various interaction modalities in AR systems in Section 8.3. AR systems architectures and case studies are detailed in Section 8.4. This is followed by a brief introduction to VR technology in Section 8.5. The important applications of VR technology in manufacturing are presented in Section 8.6 and the case studies are highlighted in Section 8.7. A conceptual framework of MR is shown in Section 8.8, followed by the conclusion and discussion in Section 8.9.

8.2 BASIC COMPONENTS AND TYPES OF AR SYSTEMS

With the support of several existing technologies, AR overlays virtual information in the real world. As a result, AR improves the operator's perception of Reality that has been supplemented with digital data. The way operators interact with their environment and carry out their daily activities will shift because of this paradigm shift.

There are five essential components in an AR system: capturing technology (CT), visualization technology (VT), processing unit (PU), tracking system, and user interface (UI). CT includes a camera or a sensor to capture the real world. VTs are the essential components of an AR system as they superimpose virtual elements in the real world. Example VTs include a mobile phone or a HoloLens®. A PU in an AR system analyses the data input and aids in visual rendering. A tracking system includes a marker, such as a QR code, used to orient the virtual information in relation to the real environment. Some AR systems can use advanced approaches such as spatial mapping and bypass a tracking system. AR systems with markers are often utilized in the industry in contrast with marker-less technologies,

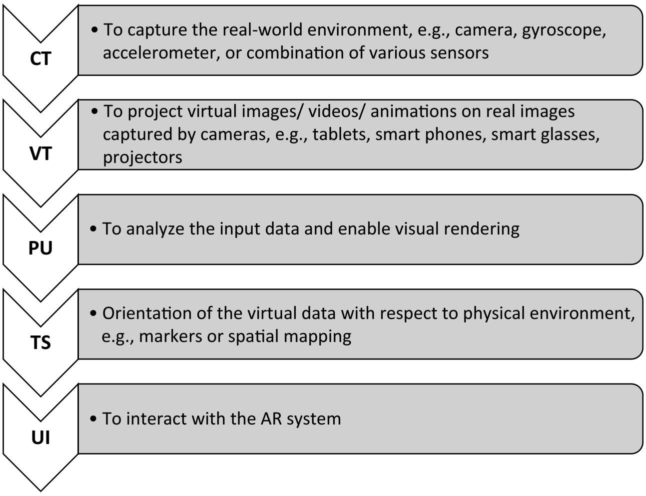

FIGURE 8.2 Basic components of an AR system.

as markers could significantly reduce the computing power in rendering virtual information. Finally, the user interacts with the AR system supported by a UI (Fraga-Lamas et al., 2018; Lee et al., 2017; Wang et al., 2016). Figure 8.2. illustrates the basic components of an AR system.

8.2.1 Types of AR Devices

Three AR devices are used: handheld devices (HHDs), head-mounted devices (HMDs), and spatial AR devices. HHDs are devices that a user can manipulate using their hands. The most common example of HHDs is mobile phones and tablets. These devices employ all the necessary components, such as a camera, display unit, processing unit, and other additional sensors. HMD is a device to wear on the head of the user, and these days they are available as part of a helmet. While using the device, the user is not entirely immersed in the virtual world as they can see both virtual and real environments intact. HHDs employ image sensors, depth cameras, holographic optical elements, holographic processing units, and microphones to support the development of AR applications. Spatial AR devices display virtual information in a real environment using video projectors, beamers, and lights. Currently, logistics and warehouse optimization projects use spatial AR technology extensively.

8.2.2 Benefits and Limitations of AR Systems

In general, HMDs are favored for assembly applications because they give the user a hands-free experience and enhance the user's perception of the real world because the view through an HMD is nearly identical to the real world. On the other hand, HHDs are used in everyday life (e.g., tablets or a smartphone). Using an HHD lessens the need for training and enables an operator to use the system directly with little to no training. HHDs are superior to HMDs from an ergonomic and financial standpoint. In spatial displays, the operator's hands are free, and they do not need to carry anything while performing their tasks. AR systems with markers are less computationally intensive compared to marker-less AR systems. Because AR applications do not require a lot of processing power, both mid-range and high-end devices can be used. Another benefit is portability, which makes it simple to move AR applications and hardware from one place to another.

The limitations of AR systems are associated with the maturity of the available technology. HMDs are uncomfortable to wear and have a limited field of view (FoV). Limited FoV compromises the operators' safety and can lead to workplace accidents (Palmarini et al., 2018). In some cases, inadequate resolution of the virtual information can cause the operator's sickness when exposed for extended periods. HMDs are heavy to wear and work for a prolonged period. Furthermore, HHDs are not portable because they require physical support to be held in place. A further drawback of an HHD system is the limited size of its UI, which restricts the amount of information that can be displayed on it. AR systems that use markers need special care concerning the maintenance of the markers. Marker-less AR systems require more computational power for object tracking in real-time.

8.3 INTERACTION MODALITIES IN AR SYSTEMS

Interaction modality is a way of sensing such as touch (haptic), voice (acoustical or auditive), vision (optical), etc. In AR, interaction modalities help users to interact with AR interfaces (Esteves et al., 2017). Currently, there are three ways to interact with AR systems: touch, touchless, and wearables. These interaction modalities are divided into input modalities and output modalities. Input modalities are for the user to give instructions to the AR system, and output modalities are for the user to receive feedback from AR systems. The AR modalities are shown in Figure 8.3.

Touch modality is not new in the manufacturing industry. Most of the existing operator panels on the mechanical systems have touch modality enabled, either with buttons or with touch screen displays.

With the development of AR technology, especially with HMDs, a new type of deictic gesture to interact with AR devices is possible (Williams et al., 2019). These gestures are mostly given mid-air with the operator's hands (Mistry & Maes, 2009). For example, raising an index finger in the FoV of smart glass can indicate that the operator is ready for a selection, and pinching the index finger with the thumb can follow the selection of a particular target.

Voice, a natural interaction modality, has been the most widely used in our daily communication. Yet, this modality is intercepted by machine noises in an industrial environment, especially on shop floors. The voice interaction modality enabled by speech recognition techniques allows the user to interact with the AR systems using voice commands (Nizam et al., 2018). Eye tracking (Liu et al., 2019) is a recent development in AR that is derived from complex algorithms that estimate the movement of the cornea and pupil of the eye in space. In an HMD powered by eye tracking interaction modality, cameras that operate at a high frame rate capture the images of the eyes. As the name suggests, screen dwelling (Qian et al., 2020) makes interaction with a system possible by gazing at the target for a specified amount

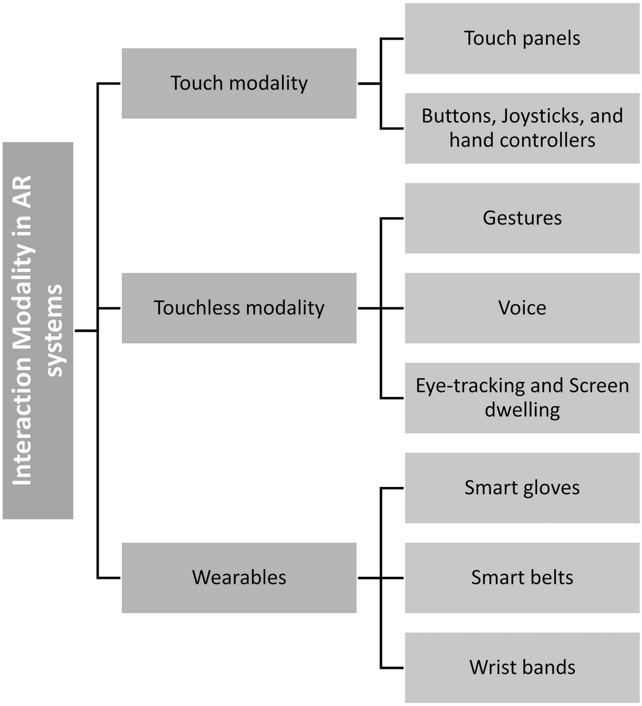

FIGURE 8.3 Interaction modalities in AR systems.

of time. The gyroscope and motion sensors of the system facilitate the dwelling interaction. Of course, dwelling is only possible by combining it with another modality, such as head, hand, or eye tracking.

Even though wearables found their way into the fitness industry and health tech, they aren't matured to be used along with AR devices in an industrial environment. However, research on wearables such as smart gloves (Hsieh et al., 2016), belts (Dobbelstein et al., 2015), and wristbands (Hu et al., 2020) is rapidly progressing for better-enhanced interactions with smart devices. This chapter presents two case studies where touch, gesture, and voice interaction modalities are employed in the AR application.

8.4 AR CASE STUDIES

All-in-one AR solutions are readily available in the market to meet a wide range of industrial needs. These solutions are expensive and, to an extent, overkill for smaller applications in manufacturing enterprises. In this section, the authors demonstrated the development of AR applications from scratch using inexpensive hardware, open-source software, and plugins. The workflow process presented in this section is attractive to the needs of SMEs as the capital expenditure required is minimal compared to off-the-shelf solutions on the market.

Both case studies solve the same problem of digitalizing the work instructions to assemble a planetary gearbox using two alternative hardware setups and features on each. In the first case study, an affordable Android system is used to develop an AR solution; in the second, a HoloLens® is proposed with expanded capabilities.

In terms of software, Unity® is the primary development engine used to create interactive 3D experiences. Besides Unity®, C# programming is used for interactions in AR applications, Vuforia® for marker tracking and orientation of virtual elements, and Autodesk® inventor for 3D modeling. Various open-source plugins are used from the Unity® store for specific operations in developing AR applications. For example, the lean touch plugin from the Unity® store enabled the touch modality in the Android AR application.

8.4.1 CASE STUDY PROBLEM

A planetary gearbox is designed by Autodesk® inventor, which contains a diversity of components and requires a number of steps to be assembled. The case studies need to simulate the real-world shopfloor scenario. Therefore, care was taken to have different assembly tasks such as screwing, fastening, circlip fixing, and bearing fitting. An exploded view of the planetary gear is shown in Figure 8.4. All the parts are 3D printed, and components such as bearings, circlips, nuts, and bolts are bought off the shelf for the assembly operation. The usage of several tools is required by including such components, which increases the complexity of the assembly process and simulates the shopfloor experience. In Sections 8.4.2 and 8.4.3, two AR applications are developed to digitalize the work instruction to assemble a planetary gearbox.

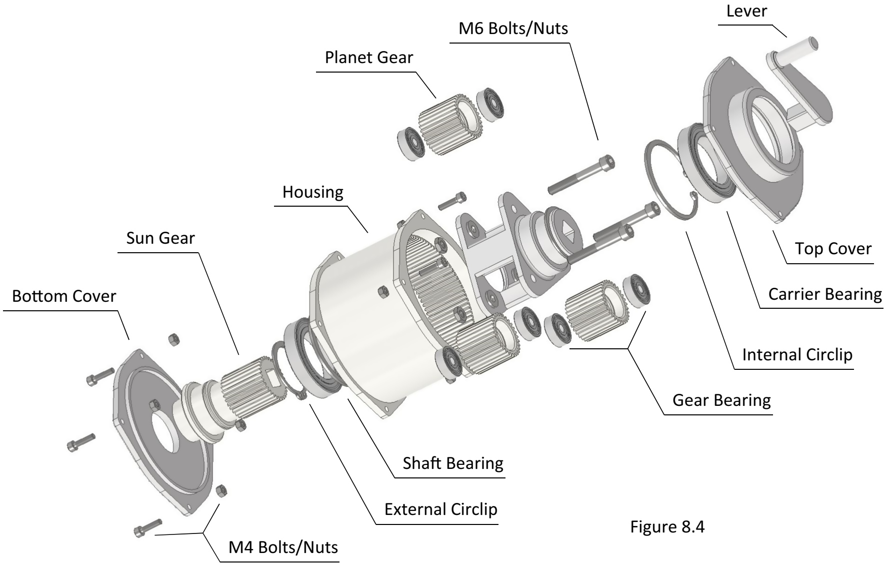

FIGURE 8.4 Exploded view of planetary gear.

8.4.2 CASE STUDY 1 – DIGITALIZING ASSEMBLY INSTRUCTIONS USING A HANDHELD AR DEVICE

This section presents the development process of digitalizing the assembly instructions to assemble a planetary gear using an HHD (e.g., a mobile phone). From the hardware perspective, a Samsung® A7 device running on the Android operating system is chosen. The device comes with all the necessary AR elements, such as a camera, processing unit, touch interface, and other useful sensors. Moreover, mobile phones are readily available, and most users feel comfortable using these devices.

From a software perspective, a framework is developed to model the abstraction first approach. As the manufacturing domain is adapting software to assist their daily operations, it is important to understand and adapt the workflow of software developers. In software development, the C4 framework (Brown, 2019) is very popular for visualizing the software elements in a simple using a lean graphical representation technique. Figure 8.5 illustrates the software framework used to design the Android

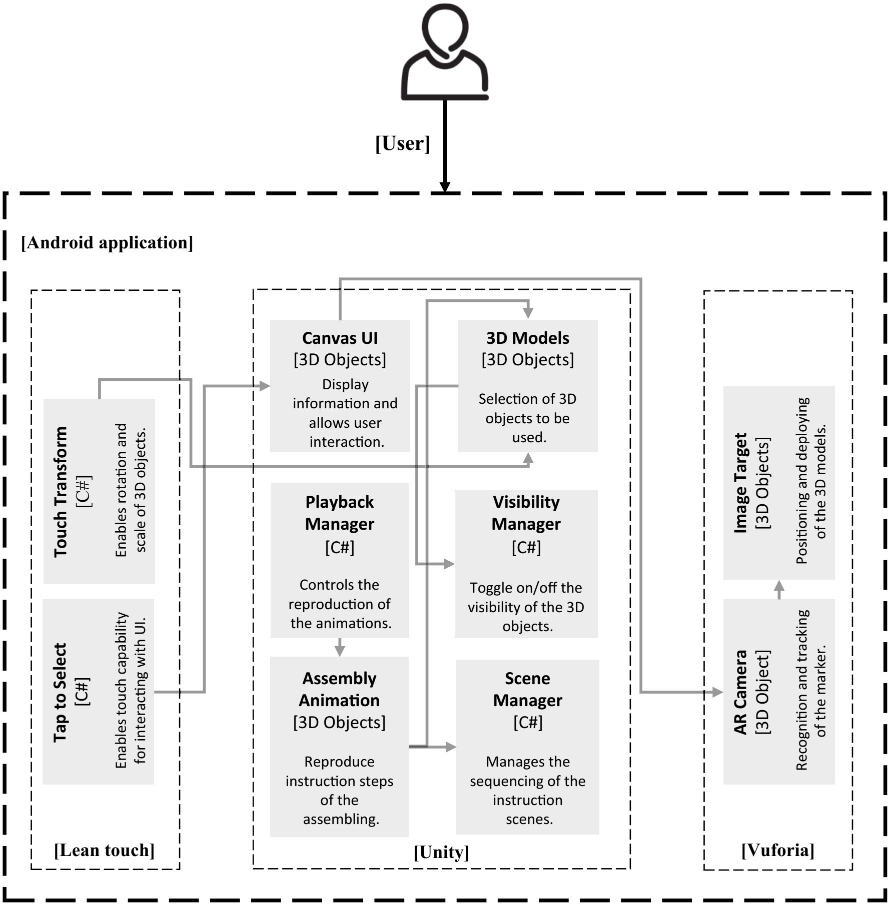

FIGURE 8.5 Software framework for mobile device (HHD).

AR application on a mobile device. The C4 framework has three layers: software system, containers, and components. The idea of a user interacting with the AR application forms the software system. Containers are executable applications, and in developing the Android application, the following containers are used: Vuforia®, Unity®, and Lean Touch. Components provide functionality, and are not separately deployable without a well-designed interface. In this application, C# programming and 3D files are examples of components.

The virtual instructions to assemble the planetary gear are shown using animations created by 3D models. The user can use the interactive buttons on the UI to reproduce, pause, replay, and navigate to the next/ previous instructions. The UI is designed such that the user can get auxiliary information about the assembly parts by tapping each part. The auxiliary information is available on demand, as having it on the UI by default is not ideal for the usability of the application. The user also can scale and rotate the animations by pinching the display unit with two fingers. Touch input modality was applied in the development of this AR application. The program is developed from the Unity® scenes containing all the necessary elements to run on it. AR Software Development Kit (SDK) from PTC (PTC, 2020) is used to convert the Unity® scenes to an executable Android application using an inbuilt plugin. In the development of the application, a fiducial marker (QR code) optimized by Vuforia® is used to track image target and orientation. Figure 8.6 illustrates the UI of the Android application.

In summary, the AR application is developed for Android devices using see-through video technology using a marker-based tracking system. Touch modality is the only input modality used for the development of this AR application. The application is

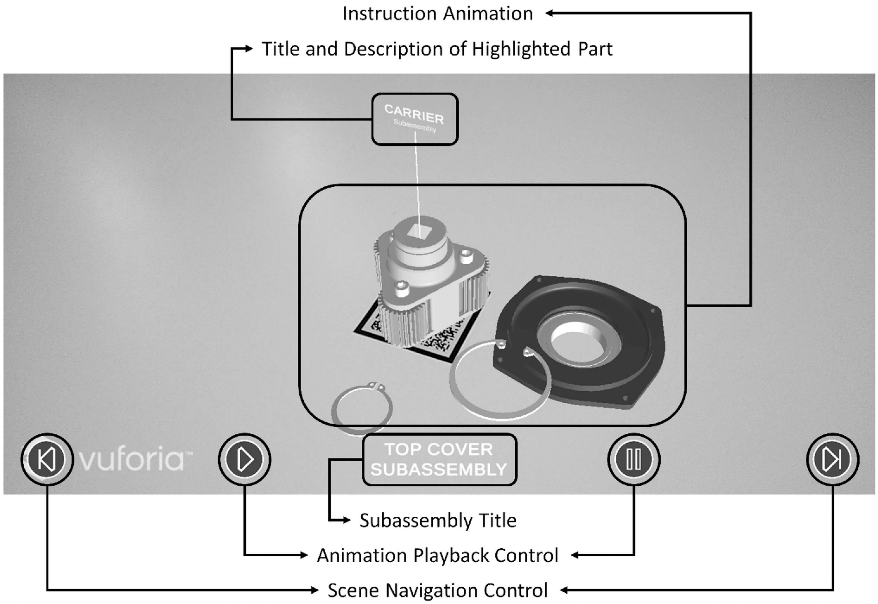

FIGURE 8.6 User Interface (UI) on mobile device (HHD).

portable to different locations on the shop floor. However, the FoV of the UI is limited by the size of the display unit of mobile devices. Visual cues such as part and tool pointers are not included in the application as it requires much more computing power and creates lags while running the application.

8.4.3 CASE STUDY 2 – DIGITALIZING ASSEMBLY INSTRUCTIONS USING A HEAD-MOUNTED AR DEVICE

Like the HHD application in Section 8.4.2, the application on HMD (e.g., ®HoloLens) delivers the digital instructions to assemble a planetary gear through several steps. The hardware used in this development process is an HMD from Microsoft® running on the Windows® operating system. HoloLens® 1 is packed with several sensors and a processing unit and supports input modalities such as gaze tracking, gesture recognition, and voice recognition. The FoV in HMD devices can be varied by head movement. This new freedom allows the implementation of several new features compared to the HHD application to help the user navigate the application. However, the user needs to be trained before using the HoloLens® as it is relatively new and unfamiliar to most users.

From a software perspective, a framework is developed just like in case study 1. Figure 8.7 illustrates the software framework used to design the Android AR application on a HoloLens®. The three layers of the C4 framework represented here are the software system (HoloLens® application), containers (Unity and Mixed Reality Tool Kit), and components. The spatial mapping feature of HoloLens® is used to detect the workplace and display instructions instead of a QR code. The voice commands from the user are translated to inputs for the HoloLens®, and this is enabled by the inbuilt Voice Manager feature of the Mixed Reality Tool Kit.

When the user interacts with the HoloLens® for assembly instructions, by default, a scene is loaded without any supplementing information. This will keep the visual and cognitive load of the user to a minimum level. However, the user can command the device using voice inputs such as “Parts,” “Tools,” “Next,” and “Previous” to get the information needed or to navigate through different scenes. The hand gesture is also enabled in the application and is limited to positioning the digital workstation on top of the real one. This is done to situate the origin of the digital system on the correct location of the spatial map; after that, it is anchored and will stay locked in position even when the application is restarted. This initial setup is done when the application is used for the first time or when the workstation is physically moved somewhere other than the initial place. This also enables the device’s portability for different workstations for diverse operations. Figure 8.8 illustrates the UI of the application on HoloLens®.

In summary, the AR application is developed for HoloLens® using see-through optical technology using spatial mapping as a tracking system. Speech and gesture modalities are incorporated into the application, validating the multimodal approach in interacting with AR devices. The application is portable to different locations on the shop floor. Moreover, the FoV of the UI is variable enabled by the head tracking feature of the device. Visual cues such as part and tool pointers are included in the application as an increased field of view allows multiple feature implementations.

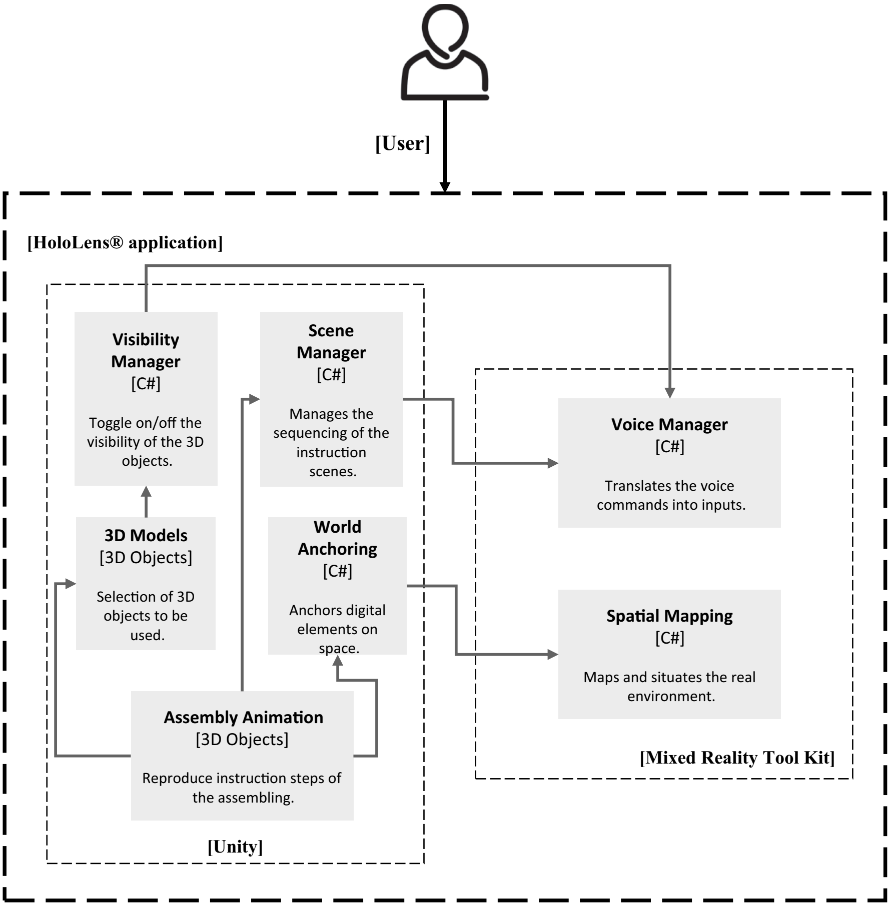

FIGURE 8.7 Software framework for HoloLens® (HMD).

8.5 VR TECHNOLOGY IN MANUFACTURING

The availability of powerful, immersive hardware and software systems has made the visualization of complex systems in a realistic virtual environment very efficient. VR is defined as an immersive computing technology that provides a unique way to interact with the ever-growing digital landscape (Berg et al., 2017). This interaction helps in depicting the behavior of complex and abstract systems in a holistic way to both experts and non-experts. The ability of VR technology to revolutionize traditional processes and working methods has been identified by large companies in the automotive and aircraft sector, especially in the topics of knowledge transfer, professional training, and new product development.

The objective of the immersive technology tools developed to experience the virtual environment is mainly to deliver information to our senses, particularly sight, hearing, and touch. Some of the most used VR tools are VR-Powerwall, cave virtual environment, and a VR-head-mounted display.

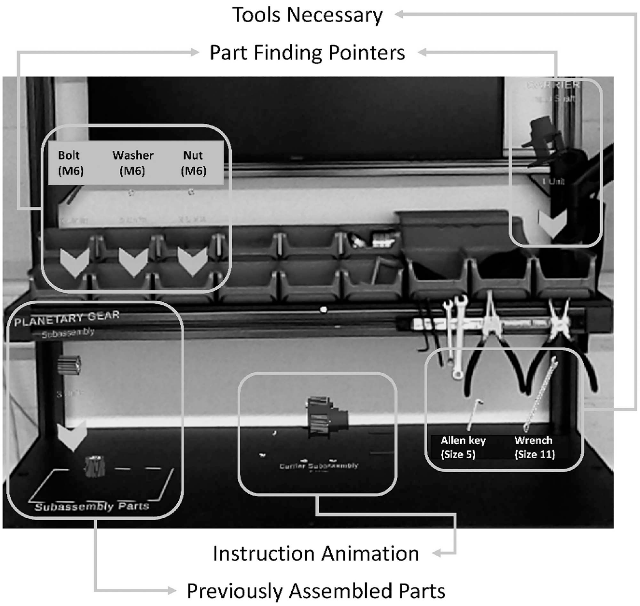

FIGURE 8.8 User Interface (UI) on HoloLens (HMD).

The rest of the sections will focus on the important applications of VR in manufacturing and the various case studies which have shown the potential of VR in manufacturing.

8.6 VR APPLICATIONS IN MANUFACTURING

VR is being used increasingly in many manufacturing applications. The various applications are explained in this section to provide the reader with the possible opportunities for using VR (Choi et al., 2015).

8.6.1 VR in Design

VR technology plays a significant role in designing and prototyping new products. The best use of VR is in the conceptual design stage, where it provides the designers with a virtual environment for designing a new product in 3D. This feature helps them in analyzing the performance of different mechanical features such as hinges, assembly, etc., which in turn will aid in evaluating the conceptual design.

Another important application of VR is seen in virtual prototyping, where the engineers can use the virtual prototype before fabricating the physical prototype to suggest improvements in the design, evaluate specific characteristics of the prototype, help in manufacturing planning, and get feedback from the potential customers in case of a new product. Generally, such applications incorporate all the different functionalities needed to realistically simulate the dynamic behavior of the product, including human interaction with the virtual environment, and consist of both offline and real-time virtual simulation.

8.6.2 VR in Manufacturing Processes

VR technology helps in understanding three different areas of the manufacturing process, namely, machining, assembly, and inspection. Machining using VR technology is used in processes such as turning, milling, drilling, grinding, and so on. They help the engineers in simulating the manufacturing processes where the user can mount the workpiece on the machine, perform direct machining operations using the corresponding tool and verify if the desired output is obtained.

Virtual assembly using VR technologies helps in making assembly-related engineering decisions as it helps the designers to analyze, visualize and implement different models without realization of the product or support process. On a larger scale, it can help in investigating the assembly process in an assembly line where the location, sequence, and type of operation can be optimized beforehand.

8.6.3 VR in Planning, Simulation, and Training

The virtual environment developed using different VR tools can lead to optimal planning of a manufacturing system with the best possible arrangement of shop floor and different machines. The comparison of different layouts/solutions considering human experiences and facts has resulted in the rapid start of several manufacturing processes.

VR-based training is among the most advanced method for training workers with the necessary manufacturing skills and processes. The virtual model of the product, plant layout, and assembly process helps the workers understand the different features associated with each field. Since the visualization and simulation are done realistically, the workers feel it is easier and faster to learn than with the conventional methods.

8.7 VR CASE STUDIES

8.7.1 Case Study 1 – VR for the Development of a Virtual Robotic Cell

Darmoul et al. (2015) developed a virtual model of a robotic cell and analyzed its functioning in a semi-immersive virtual environment to provide a feasible layout planning for setting up the real robotic cell. Through this work, the authors demonstrated that saving time and effort while designing such robotic cells using VR technology was possible. They were able to assess various layouts and configurations without the risk of damaging the system. They used the virtual robotic cell for layout planning and set up a real robotic cell in an advanced manufacturing institute, King Saud University, Saudi Arabia.

To achieve their goals, they used a combination of hardware equipment and software architecture consisting of CATIA for the CAD model generation, InterSense IS-900 wired tracking devices for head and hand tracking, pro-engineer, division mockup, and so on. The developed robotic cell was used for training industrial workers and academic researchers to demonstrate the advantages of VR technology and its potential for the manufacturing industry.

8.7.2 CASE STUDY 2 – VR-BASED CONFIGURATOR OF INTERIOR ACCESSORIES FOR FIRE TRUCK

Researchers from the University of Applied Sciences Karlsruhe, Germany, in collaboration with company Rosenbauer Karlsruhe GmbH & Co. KG, used VR technology to develop a configurator of interior accessories for a fire truck (Bellalouna, 2020). This helped the company decouple the determination of the firefighting equipment position from the production of the fire truck. The author identified the necessary functions to be implemented in the VR application by organizing several workshops with the sales engineering departments of the company and different fire departments. Some of the necessary functions were VR libraries containing all the firefighting accessories, different fire truck models, the configuration of the equipment shed, a function to determine the equipment weight, center of gravity, and axle load, and finally, an option to create the bill of materials. The VR application developed was evaluated to check its usability for further business processes, and the following points were inferred:

a. The users found the functions to be intuitive and also allowed a cognitive configuration process.
b. The application helped in creating a realistic VR environment with a high emersion ability without any restriction.
c. The application helped in identifying conflicts between design and customer requirements during the early product lifecycle phase.
d. One weak point of the system was that the successful VR-based configurator only allowed a single-user application. In contrast, successful deployment of the VR application requires multi-user involvement.

8.7.3 CASE STUDY – IMPLICATIONS OF VR TECHNOLOGY ON ENVIRONMENTAL SUSTAINABILITY IN MANUFACTURING INDUSTRIES

An interesting case study was carried out by Chen et al. (2021) with an international automotive company with a research and development center in Sweden and manufacturing plants in China to explore the implications of VR technology on environmental sustainability in manufacturing industries. They developed a VR demo of the welding process in a manufacturing environment in China to be used by the users from the development center in Sweden. In addition to the VR demo, they used various tools such as customer experience feedback, interviews, and questionnaires.

They showed that the users were able to communicate more efficiently about the product design as the VR application offered them the product view from different angles and with more details. This improved communication efficiency enabled constant and frequent dialogue between developers and implementation sites and potentially reduced the number of travels between China and Sweden.

Due to the possibility of performing product and process design verification from Sweden, this demo application could contribute to environmental sustainability with less CO_2 emissions generated from international trips.

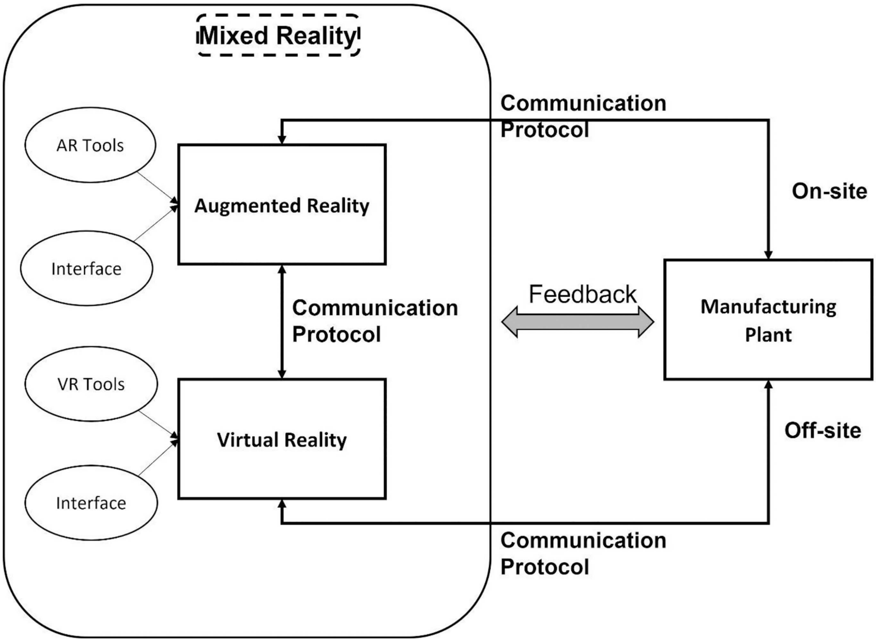

FIGURE 8.9 Conceptual framework for integrating MR technology in a manufacturing plant.

8.8 CONCEPTUAL FRAMEWORK FOR MR TECHNOLOGIES

MR, like several other Industry 4.0 solutions, draws in data from the tools available to create virtual realities the workers can use to augment their work. Implementing MR technologies by using VR and AR for both on-site and off-site operations in a manufacturing sector can help improve the working conditions for the workers, have better control over the plant operations, and integrate Industry 4.0 technologies for their production activities. A simplified conceptual framework for MR technology in manufacturing is shown in Figure 8.9.

8.9 DISCUSSION AND CONCLUSION

MR technologies play a very significant role in complex product development and production processes. Due to the advancement in different immersive technologies, MR has found its way from many high-tech industry sectors to SMEs as well. However, there are several challenges that need to be addressed to reach its actual potential in the field of manufacturing.

One of the topics that will strongly influence the future of MR applications development is spatial registration technology, which can combine the virtual world and the real world through a proper relationship of relative positions. This will help the user in efficient localization in the MR environment and improve the performance of the MR application. The second challenge is the development of a user-friendly interface for MR applications that are affected by aesthetics and ergonomics. One big problem in using MR technology at a large scale is the heavy display equipment, which is unsuitable for a production line. The alternative solution of using mobiles or smartphones also has a limitation: the workers must perform their work simultaneously using the MR application. During such times, fixing the mobile phone in the workplace or using a lightweight advanced HMD could be a good option. The next challenge is in developing MR applications for multiuser collaboration. Generally, a fully functional manufacturing line consists of a line manager, engineers from different disciplines, operators, and technicians. In such cases, it is of utmost importance to provide an MR platform enabling helpful collaboration, information sharing, and real-time communication among the different users.

Despite their limitations, the potential of MR technology for manufacturing is enormous and is becoming increasingly mature through the innovation of related technologies. Combining the benefits of mixed Reality with other Industry 4.0 tools will enable the manufacturing sector to bring different teams together to increase their performance, efficiency, and market share.

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