Manufacturing Assembly Simulations in Virtual and Augmented Reality

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Abstract:
Virtual Reality (VR) and Augmented Reality (AR) technologies have been well researched for decades, and recently they have been introduced to the consumer market and are being applied to many fields. This chapter focuses on utilizing VR/AR technologies for assembly simulations in advanced manufacturing. First, some basic terminologies and concepts are clarified, and the VR/AR technologies are outlined to provide a brief introduction to this topic. State-of-the-art methodologies including modeling, sensing, and interaction that enable the VR/AR assembly simulations are then reviewed and discussed. This is followed by assembly examples applying the technologies, and a hands-on case study is used to provide a demonstration of and practical guide to implementing a VR/AR assembly simulation application. Finally, the limitations and challenges of current VR/AR technologies and future research needs are discussed.

1.1 Introduction

Virtual Reality (VR) and Augmented Reality (AR) technologies have been studied and prototyped in labs for decades without much public attention. However, in recent years, they have been introduced to the consumer market and are being applied to a wide range of fields due to the cost reduction of VR/AR hardware and the algorithm improvement of software. In the manufacturing assembly area, VR/AR technologies have been used to simulate the costly processes beforehand and help train the workforce using a more interactive way. This section introduces some basic terminologies and concepts to provide a brief introduction to this topic.

1.1.1 *Virtual Reality (VR)*

Although Virtual Reality (VR) is one of the current technology buzzwords, it is not a brand-new concept and actually has a history over 60 years. The Sensorama simulator [35] invented in the 1950s is believed to be the first functional VR machine that could provide users a realistic experience. From then on, many researchers have worked on this area, and various prototypes have been developed.

The term VR refers to a series of techniques for humans to visualize, manipulate and interact with computers in a realistic virtual environment, which provides an interactive graphics interface enhanced by non-visual modalities such as auditory, haptic, and smell feedback to enable the user feeling the presence of a real physical environment [9, 15, 39]. As shown in Fig. 1, an ideal VR system can generate a virtual environment for the user by providing the five senses, including sight, hearing, touch, smell, and taste. There are different VR systems such as CAVE VR systems [21, 81], desktop VR systems, and head-mounted VR systems.

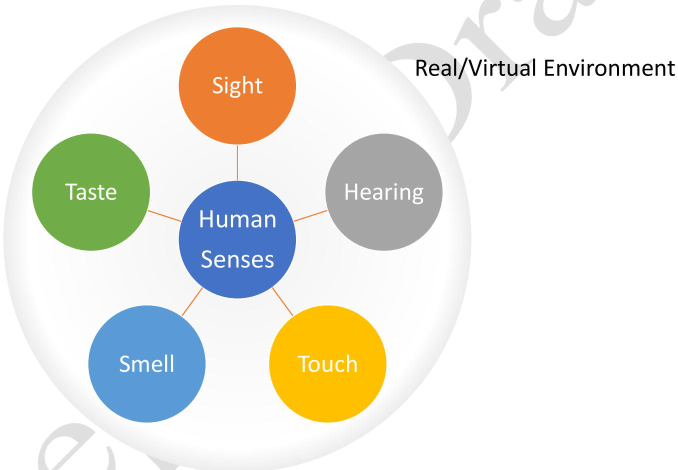


Figure 1: Five human senses to perceive the real/virtual environment.

The cost reduction of hardware and the algorithm improvement of software over the years have been gradually pushing the VR technology from labs to the consumer market. In 2012, the company Oculus VR was founded and announced an affordable VR headset, which makes VR experiences easily accessible to consumers. Two years later, Facebook acquired Oculus VR for more than 2 billion dollars [19], which further boosted the VR market and attracted lots of companies, researchers, and entrepreneurs to enter this field. Meanwhile, the VR technology has been employed to provide various solutions to all kinds of industries.

1.1.2 *Augmented Reality (AR)*

For VR, a virtual environment is generated to provide users with fully immersive experiences. For Augmented Reality (AR), instead of generating a virtual environment, the real-world environment is “augmented” by computer-generated perceptual information, ideally across multiple sensory modalities, including visual, auditory, haptic, etc., which is how the term AR is originally coined. The augmented information is appropriately overlaid onto the physical environment and presented in the user’s view through an AR device, such as a hand-held display or a see-through Head Mounted Display (HMD). To have the optimal correlation between the virtual information and the physical world, it is required to keep sensing the physical world and tracking the AR device in the spatial context.

In addition to AR, the term Mixed Reality (MR) has also been used in the literature to represent the VR related technologies that involve the merging of real and virtual worlds. Milgram et al. [54] defined a “virtuality continuum” (see Fig. 2) and divided MR into AR and Augmented Virtuality (AV). For simplicity and following the common terminology, this chapter emphasizes AR and it has the same scope as MR shown in Fig. 2.

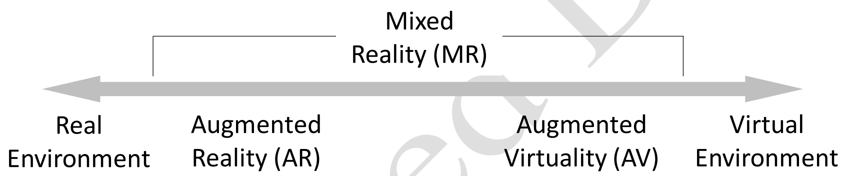


Figure 2: Milgram’s “virtuality continuum” [54].

There are some commercial AR devices currently available in the market. Google Glasses was first released in 2013, which is an AR product that needs to be paired with a smartphone. Microsoft released its AR glasses HoloLens in 2016. It is a standalone AR device that does not need to connect to a computer or smartphone. Recently, more smartphone-based AR technologies have been developed and are increasingly popular in a wide range of fields.

1.1.3 *Manufacturing Assembly Simulation (MAS)*

To keep pace with the vibrant technology revolution planned in the Industry 4.0 era, more and more manufacturers have been reconsidering their assembly systems. More flexible and efficient assembly methods and strategies have to be developed to meet the dynamic needs of customers and the shortened product lifecycle. In such a context, the current assembly systems must be upgraded in order for products to gain success and maintain competitiveness in the market. These goals could be achieved through assembly simulation in a virtual environment before launching a real factory to identify potential problems without the use of physical mockups, thus shortening the design cycle and improving product quality.

With the help of VR/AR technologies, which puts humans in the loop and takes the human's experience at the first place, the assembly process can be simulated in a more immersive, interactive manner, especially for worker-involved assembly tasks. Also, assembly training can be conducted in VR/AR environments to train workers and improve their skills. The main building blocks needed for assembly simulation in VR/AR are briefly described below.

Modeling. One of the primary tasks for developing a MAS application is to create the digital models. The 3D model of a physical part can be generated using CAD software or a 3D reconstruction process with the acquisition of part geometric data in digital form from an existing physical part. Unlike gaming VR/AR, the digital 3D models in the aspect of MAS should be accurate in dimensions, realistic in physics, and functional as real parts in the virtual environment.

Environment Sensing & Pose Estimation. In VR, we need to track the user's pose to change the digital contents in the user's view accordingly to make the user feel that he/she is in the real world performing a real task. In AR, sensing the environment and tracking the user's pose is even more crucial, because it requires real-time registration and tracking to realize the optimal mapping between the virtual world and the real world.

Interface and Interaction. In VR/AR, the visual interface is the most important one. In addition, auditory and haptic interfaces, and even smell and taste interfaces can be used to further augment the visual interface to make the user feel fully immersed in a VR/AR environment. In terms of interaction, how the user manipulates and interacts with the virtual objects as he/she does with physical objects should be developed.

1.2 Methodologies for Assembly Simulations in VR/AR

This section reviews and discusses the state-of-the-art methodologies that enable VR/AR manufacturing assembly simulations.

1.2.1 *MAS modeling*

Creating digital models for virtual objects is one of the primary tasks in MAS. The conventional approach for building 3D models is to use commercial CAD software, such as NX [47], SolidWorks [25], and CATIA [24], to create CAD models for virtual objects. Another approach is reconstruction of 3D models from real objects, which starts with data acquisition from physical objects in a real environment and ends with digital models representing these objects on the computer [64]. With this approach, the often time-consuming modeling process done by human designers can be automated, which significantly reduces the development time and cost. As shown in Fig. 3, the process of 3D model reconstruction includes data acquisition, data processing, positional registration, modeling, and rendering [27, 28].

Figure 3: Process of 3D model reconstruction.

To create a 3D model from a real object, the first step is to acquire the digital data of the 3D object's surface. Many data acquisition techniques have been developed, and they can be categorized as mechanical and optical approaches. There are some other methods such as ultrasonography, radiography and Magnetic Resonance Imaging (MRI) for data acquisition purpose. They are not discussed here as they are costly and not commonly used for MAS applications. A classification of these techniques is illustrated in Fig. 4. Mechanical data acquisition is a mature and well-established method that has been used for many years in reverse engineering and industrial inspection. It utilizes a Coordinate Measuring Machine (CMM) or a robotic arm to measure the coordinates of points on the object's surface to acquire the shape. Currently, optical methods are more widely used as they can provide non-contact, relatively more efficient data acquisition. In addition to acquiring the shape, they can capture the appearance as well, which further reduces the time consumed for modeling and rendering. The optical methods can be divided into passive and active ones. Passive methods do not emit light onto the target object, and the shape of the object is estimated from the perceived images, using techniques such as shape from shading [36], shape from silhouette [18, 51], and stereo vision [30, 31, 69]. Active methods often project light onto the target object before sensing. The structural light based method [67] projects a certain pattern onto the object and then retrieves the depth information by analyzing the distorted pattern from the captured image. The Time-of-Flight based method [22] measures the time taken for the light to travel from the transmitter to the object surface and back to the receiver, based on which the depth information can be calculated [46]. The light source can be a laser or a near-infrared LED.

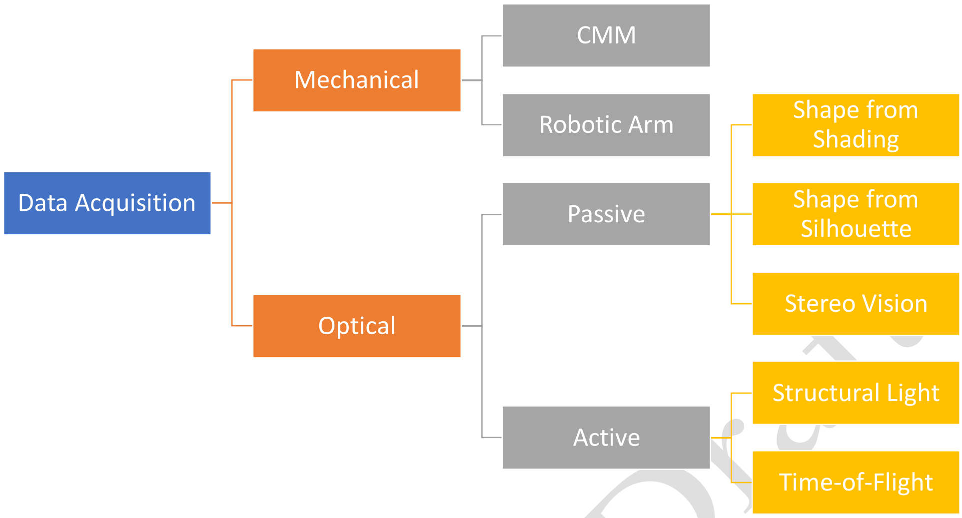


Figure 4: 3D model data acquisition techniques for MAS.

After the procedure of data acquisition, the 3D model of the object can be generated by surface reconstruction, the objective of which is to determine the object's surface geometry from a given finite set of measurements. Usually, the acquired data are disorganized and noisy. Furthermore, the surface may not have a specific topological type and could be arbitrary in shape. The steps to generate 3D models from the acquired digital data include the following [64]: (i): Pre-processing: Erroneous data are removed, and the noise in the data is smoothed out; (ii) Determination of the surface's global topology; (iii) Generation of the polygonal surface; and (iv) Post-processing: Edge correction, triangle insertion, hole filling, and polygon editing are used to optimize and smooth the shape.

The data acquisition devices are usually called 3D scanners. Besides expensive industrial scanners, there are some low-cost 3D scanners in the market that are affordable and suitable for MAS development, such as Microsoft Kinect [53], MakerBot Digitizer [50], and 3D Systems Sense [1], which are shown in Figure 5. The 3D model reconstruction software is also provided to generate the digital models from 3D scanning.

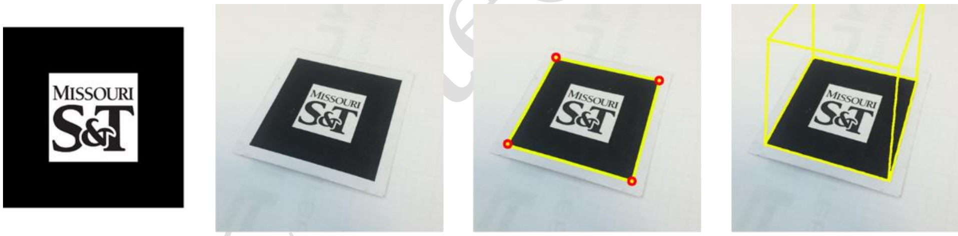
Figure 5: Example low-cost 3D scanners for data acquisition [53, 50, 1].

1.2.2 *Sensors and sensing technologies*

This section reviews different kinds of sensors and sensing technologies for environment perception and human pose estimation, including marker-based and marker-less tracking technologies. Human pose estimation methods are also reviewed.

1.2.2.1 *Marker-based tracking for AR*

Real-time tracking is one of the crucial tasks in AR applications because the generated virtual information needs to be superimposed upon the real world with intuitive mapping in real time to avoid causing discomfort for the user. Marker-based tracking is the most widely used method for real-time tracking due to its ease of implementation and high accuracy. As illustrated in Fig. 6, a predefined marker is captured by a camera and it is detected and tracked on each frame. Then the position and orientation of the marker relative to the camera is estimated. Finally, a virtual model is rendered using the estimated pose. There are some commercially available tools for marker-based tracking, such as the classic ARToolKit [42] and Vuforia [82], which will be discussed in detail in Section 1.4.1.



(a) Marker (b) Video capturing (c) Marker tracking (d) Model overlaying

Figure 6: Illustration of marker-based tracking for AR.

1.2.2.2 *Marker-less tracking for AR*

Since markers can be designed with optimal tracking patterns, marker-based methods are very accurate for camera pose estimation. However, These methods are not convenient in some cases, especially for objects with small size or uneven surface, which is not feasible to mount markers on. Furthermore, the tracking can be lost when the marker is occluded. Therefore, researchers have developed marker-less tracking methods for AR technology [48, 83]. Instead of detecting a specific marker, a marker-less method extracts features from the real environment, such as intersections of walls and floors and edges of an object, then these features are used to estimate the object's position and orientation.

Simultaneous Localization and Mapping (SLAM) technology is a technology initially developed in the robotics field for self-navigation, which gets the sensing data (e.g., Lidar, odometer, GPS, visual) to construct or update a map of an unknown environment while simultaneously keeps track of an agent's location within this map [16, 26, 72]. A SLAM technique using cameras is also called visual SLAM (vSLAM) because it only uses visual information [72]. SLAM is getting increasingly attractive in recent years due to the prevalence of domestic robots, self-driving cars, and smart drones. Since it is useful for perceiving and understanding the real physical world, researchers and companies have been utilizing SLAM for AR applications. As examples, Apple released their ARKit [5] for AR developers in 2017, and Google launched ARCore [32] in 2018 to replace their previous experimental AR project Tango [41]. ARKit and ARCore both incorporate SLAM algorithms to detect and track planes such as floors and walls in the real-world scene, then the digital content can be overlaid onto these planes. At present, SLAM is an active research area with lots of new algorithms being developed.

1.2.2.3 *Human pose estimation*

Human pose estimation is very useful for human-computer interaction in the VR/AR environment. According to the sensing techniques used, human pose estimation can be classified into two categories: optical and non-optical [46]. Optical methods utilize optical cameras to capture digital images, from where the poses are estimated.

(1) **Marker-based**. Marker-based methods need specific trackable markers to be mounted on the human body to represent the positions of the body part. These markers can be passive markers, which are usually small balls coated with a retro-reflective material. The tracking area is illuminated by an Infrared (IR) light and an IR camera is used to capture the markers. Companies such as OptiTrack [62], Vicon [80], and ART [7] have such passive optical tracking systems that are commercially available. The markers also can be active markers, which are IR LEDs and emit IR light by themselves. An IR camera is used to capture the markers. The Wiimote controller from Nintendo uses such techniques for tracking the player's pose. These systems can use the same marker tracking algorithm as the passive marker systems but are much less expensive than the passive maker systems like OptiTrack. Zhu et al. [91, 92, 93, 94] developed a low-cost assembly simulation system using Wiimote for tracking.

(2) **Marker-less**. A marker-based system can achieve high accuracy because the markers are designed and optimized for tracking purpose. However, it has

shortcomings such as inconvenience in setting up the tracking system and movement interference with the attached markers. Marker-less tracking provides non-invasive solutions to address these issues that marker-based methods have. Microsoft Kinect [53] falls into this category and is popularly used. It has a depth sensor to perceive the image depth, from which the skeleton-based human pose estimation is calculated. Some other depth cameras are commercially available, such as Intel RealSense [37] and Structure Sensor [58]. The recent unprecedented development in the artificial intelligence (AI) area, especially deep learning, makes it possible to accurately estimate the human pose directly from a digital image without the help of depth information. OpenPose [17, 70, 85], initially released in 2017, is the first real-time multi-person system to estimate the human pose from a single image. It can detect human body, hands, and facial key points. OpenPose is a promising solution for human pose estimation because it does not need special cameras, but it is computationally intensive and relies on high-end GPUs to realize real-time human tracking, which is one of its limitations.

(3) **Non-optical**. Non-optical sensors also have been used to estimate the human pose. A magnetic tracking system, such as MotionStar developed by Ascension Technology Corp. in 1997 [8], calculates an object's position and orientation based on the earth's magnetic field. It has some drawbacks, e.g., it may be interfered by metallic objects in the tracking area. An inertia-based tracking system, such as Moven from Xsens Corp. [88], uses accelerometers and gyroscopes to capture the human body's movement and estimate the human's pose. It does not measure positions directly, thus accumulated errors may occur. An acoustic tracking system uses the time-of-flight technique to estimate the position of the emitter relative to the receivers. The emitter is attached to the body and the receivers are mounted at known location in the environment.

(4) **Sensor fusion**. To compensate for the shortcomings of each method, sensor fusion methods integrating different modalities have been developed. Researchers at the Missouri University of Science and Technology used a Kinect to provide skeleton information and a Myo armband to provide inertial and surface electromyography (sEMG) measurements. Then a multimodal deep learning method was used for worker behavior understanding, achieving promising results for future endeavors [4, 74].

1.2.3 *Human-computer interface for rendering and interaction*

Human-computer interfaces provide the user with different visual, haptic and auditory sensations, which play a vital role in a virtual assembly system for increasing the degree of immersion in the VR/AR environment. Figure 7 shows a typical VR/AR system configuration with physical input and output devices that transmit information between the user and the environment. These sensing technologies are essential to the realism of the VR/AR system. The critical technologies addressed here include visual interface, auditory modeling and rendering, and haptic modeling and rendering.

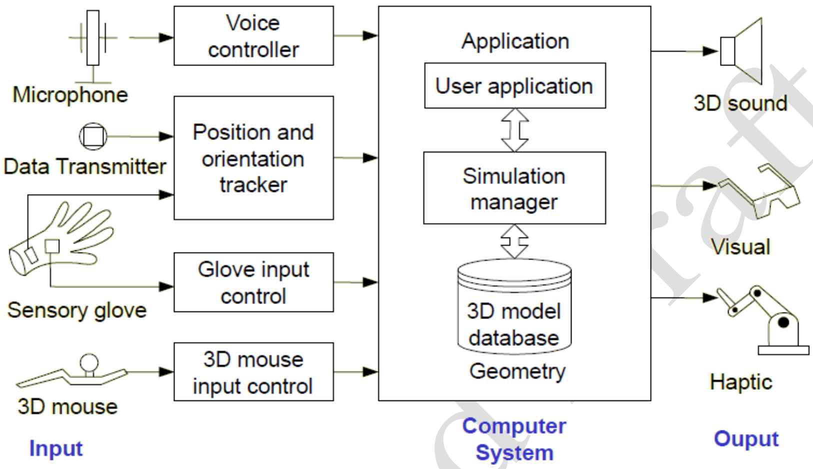


Figure 7: Typical VR/AR configuration with human-computer interfaces [46]

1.2.3.1 *Visual interface*

Visual interface is the most import interface in VR/AR. There exists different hardware providing visual interfaces, such as desktop displays, hand-held displays, projection displays, and Head Mounted Displays (HMD) that have been the mainstream due to the fully immersive experiences they provided. VR HMDs can be divided into three classes, tethered HMDs that need to be connected to a PC or console, mobile-dependent HMDs that need to attach onto a smartphone, and standalone headsets that do not need to be connected to other devices. Figure 8 shows three VR glasses available in the market that fall into these three classes and their costs range from $100 to $500. Some of the mobile-dependent products cost less than $100, which are affordable to most consumers. AR HMDs are relatively more expensive than VR HMDs because they require more complicated optical designs to realize the see-through ability. Figure 9 shows three AR HMDs in the market. The selection of visual hardware for a given application should take into consideration of the resolution, update rate, field-of-view, head tracking accuracy, latency, etc.

Figure 8: VR headsets of Sony PlayStation VR, Oculus Rift, and Google Daydream (from left to right) [34].

Figure 9: AR headsets of Microsoft HoloLens, Magic Leap One, and Google Glasses (from left to right) [52, 49, 33].

1.2.3.2 *Auditory modeling and rendering*

Audio clues can be used to augment visual interfaces for assembly simulation in VR/AR. Auditory rendering is especially helpful when haptic feedback is not available. Physics-based sound modeling is too computationally expensive for real-time rendering required in virtual assembly. Synthetic sound can be used to approximate the real sound generated from the physical assembly, making the simulation more realistic. Spectral modeling can be used as the basis for sound synthesis in virtual assembly [57, 87]. Sound generation using deep learning methods also can be used in this case [79].

In the virtual environment, a sound generator can be attached to a virtual object to generate 3D audio for auditory rendering. 3D audio can provide listeners a spatial hearing experience that enables them to sense where they are relative to the sound sources, further immersing them in the virtual world.

1.2.3.3 *Haptic modeling and rendering*

Haptic devices provide force or tactile feedback to the users can further improve the realism besides visual and auditory sensations. Such devices usually are embedded with sensors and actuators to measure the user's contact position with a virtual object and apply force or other haptic feedback to the user at the contact position. The current haptic devices can be classified into three categories: (1) handheld devices such as the Touch from 3D Systems [2] that has been used widely as a force feedback device; (2) hand wearable devices such as the Sense Glove [68] which provides feedback to individual fingers to simulate how the users interact with the real objects; and (3) haptic suits such as the Teslasuit [75] which can provide haptic feedback to the body covered by the suit. These haptic devices have some drawbacks such as having strict geometry, placement and workspace requirements, and being cumbersome for wearing, which limit them from being widely used.

Figure 10: Haptic devices of 3D System Touch, Sense Glove, and Teslasuit (from left to right) [2, 68, 75].

1.3 Application and Examples of MAS using VR/AR

Manufacturing assembly simulation using VR/AR can provide intuitive, immersive and interactive solutions for manufacturers to improve the capability and efficiency of the various assembly processes, covering assembly design, process verification, and workforce training.

Many companies have utilized MAS with VR/AR in their assembly processes and greatly benefitted from it [65]. For example, in the automotive area, Toyota [76] develops an interactive virtual learning system using VR technology to train their assembly line workers. The trainee is immersed in a virtual assembly line environment wearing an HTC Vive headset. During the training session, the trainee is guided by step-by-step assembly processes and interacts with the virtual object using the controllers. The Volkswagen Group, collaborated with the VR studio, Innoactive [96], has launched a plan of bringing VR training to 10,000 employees, which includes over 30 VR training experiences covering tasks from vehicle assembly, new team member training, to customer service [95]. Other companies like Tesla [14], Mercedes-Benz [100], BMW [101], Volvo [13], Ford [20], and Bentley [10, 11] also apply VR/AR in their factories to improve the assembly workflows. Compared with traditional training methods using paper manuals, such training systems not only can benefit the trainees with more motivational, personalized and intuitive training experience but also can benefit the manufacturers with reduced training cost, improved training efficiency and excellent scalability.

In the aerospace area, Boeing has been using VR/AR in various tasks, such as wing assembly tasks, wiring tasks, and some specialized manufacturing tasks, to help improve training efficiency, reduce design errors, and speed up maintenance processes. With the help of a Microsoft HoloLens providing the assembly instructions to the trainees, Boeing showed that this approach can shorten training time by 75% per person [6, 12, 43]. Similarly, Airbus [3], Rolls-Royce [103] and Lockheed Martin [102] also reported benefit from VR/AR utilization.

Almost all the leading industrial manufacturing companies, such as Siemens [97], Bosch [98] and Dassault Systems [99] have been actively seeking opportunities to apply the VR/AR technologies to industries.

A typical MAS application in VR is shown in Fig. 11, which is a MAS scenario of seat mounting in VR developed by Bentley Motors and OPTIS [10, 11, 61]. The native CAD models are imported into the virtual environment and haptic feedback is generated when an operator’s hand collides with a virtual object. The haptic feedback gives car makers a way to simulate and analyze where clashes and collisions might occur during the worker’s operation, and find out the optimal possible manufacturing and installation protocols. Multiple markers are attached onto the operator’s body for motion capturing and tracking.

Figure 11: A operator wearing an Oculus headset for immersive VR and attached with multiple markers for motion tracking (Image courtesy of OPTIS) [11].

AR technology allows the operator to see the real environment with virtual information superimposed upon the physical world. This has been popular in AR-assisted assembly training and guidance [66, 89, 90, 84]. AR also has been applied to other assembly related tasks, such as manual assembly station planning [63], assembly workplace design [59], and assembly constraint analysis [60].

A typical MAS in AR developed by DAQRI [23] for workforce training and guidance is shown in Fig. 12, which is a control module in an assembly task. During the assembly task, the instruction information, such as which item to pick and which tool to use, is overlaid onto the operator's view through an AR helmet. The operator can follow the instructions step by step to get familiar with the assembly sequence and acquire assembly skills. The virtual instructions can be multimedia including text, image, video, voice, etc. The task completion status is also computed and visualized.

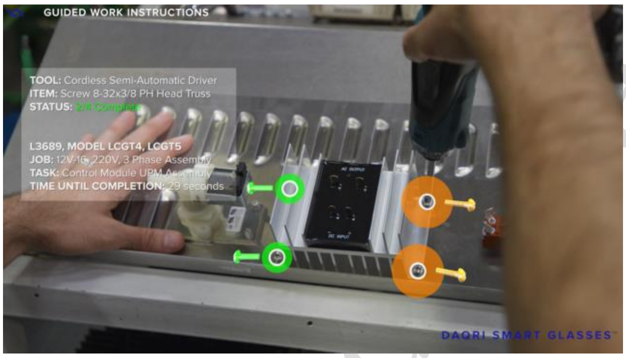


Figure 12: An AR guidance scenario from DAQRI [23].

1.4 A Case Study

This section presents a case study to provide a practical guide to implementing an AR assembly simulation application. In this case study, AR instructions are developed to guide the user in a spindle carriage installation task [38]; see Fig. 13. Hand interaction with virtual objects is explored using a Leap Motion Controller [45]. The performance comparison between AR guidance and traditional manual guidance is also presented.

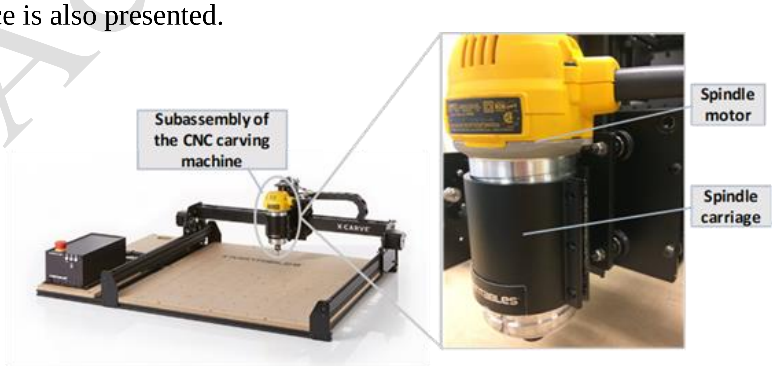


Figure 13: The spindle subassembly of a CNC carving machine.

1.4.1 *Available tools*

There are various tools that can be used for developing AR MAS applications. Some commonly used ones are introduced as follows:

Unity. Unity is a game engine developed by Unity Technologies that allows its users to develop games [77]. The engine can provide various visual effects including 2D and 3D graphics, textures, lighting and shading. The users can create a scene by importing customized CAD models with texture rendering. The engine platform supports scripting via programming languages such as C# and JavaScript.

Unreal Engine. Unreal Engine is a game engine that was first brought to the gaming platform in 1998 and has been widely used [78]. The engine is programmed in C++ and is available for different operating systems.

ARToolKit. ARToolKit is a library that can be utilized for AR application development and was originally developed by Dr. Hirokazu Kato. It is being supported by multidisciplinary institutions across the country [42]. The library can provide AR rendering through camera pose estimation and target tracking.

Vuforia. Vuforia is a Software Development Kit (SDK) for AR development [82]. It provides the functionalities of target recognition and tracking, enabling its users to superimpose 3D digital contents with respect to the world coordinates as 2D image registration for a composite view. The user can define the trackable marker for maker-based AR by importing the desired image target for augmentation with different configurations.

Wikitude. Wikitude SDK combines target recognition, tracking, and simultaneous localization and mapping (SLAM), as well as Geo-location, for various AR development engines and configurations across Android and iOS [86].

ARKit. ARKit from Apple is a platform for building AR iOS applications. It provides object detection and mapping functions for marker-less tracking, enabling the user to directly overlay information onto the environment with different geometries [5].

ARCore. ARCore is an AR platform from Google. It integrates three main top-notch elements, i.e. motion tracking, environmental understanding, and light estimation [32]. ARCore provides a wide variety of features and functionalities with different APIs and can be deployed on both Android and iOS devices.

In this demonstration project, the application is developed using Unity with the support of Vuforia SDK due to its fundamental usability and accessibility for AR implementation.

1.4.2 *Modeling*

In this case study, NX is chosen as the CAD software to build the 3D digital model for the spindle carriage. Figure 14 shows the created CAD model of the spindle carriage in NX [104].

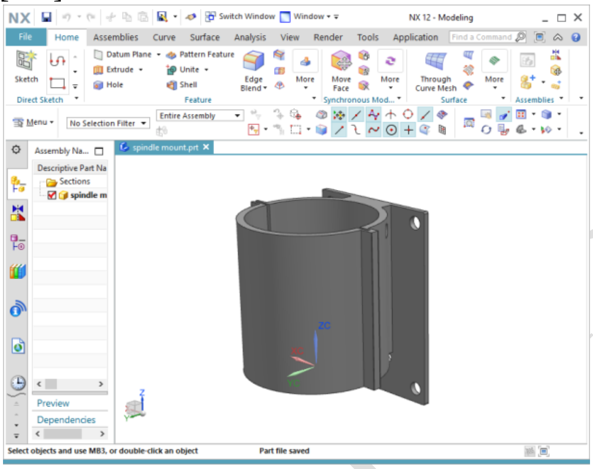


Figure 14: The CAD model of the spindle carriage.

Once modeling is finished, an AR assembly scene in Unity can be created by importing CAD models into the scene as Unity game objects either through the drop-down menu as shown in Fig.15 or using drag-and-drop to the “Assets” panel. The imported CAD models would then be categorized as game objects and be sorted on the hierarchy panel once they have been assigned to the scene. Multiple static and dynamic features can then be added to each of the game objects with different settings and parameters.

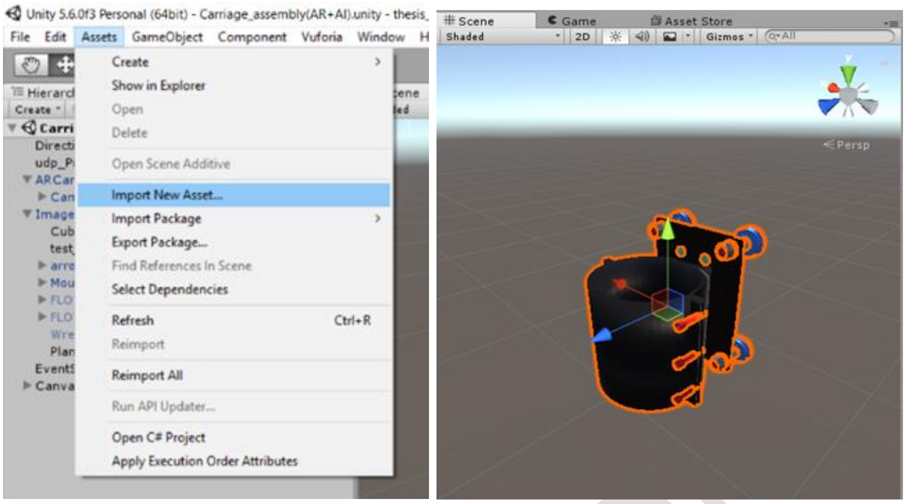


Figure 15: Importing CAD model of spindle carriage to Unity.

1.4.3 *AR realization*

The AR guidance function is achieved using Vuforia SDK in the Unity environment. The AR composite view can be realized by utilizing Vuforia prefabs and the computed target database imported from the developer portal in which the user can upload image patterns for target markers, as well as visualize the augmented contents according to the quality of the computed features. Figure 16 shows the workflow of Vuforia prefabs in Unity.

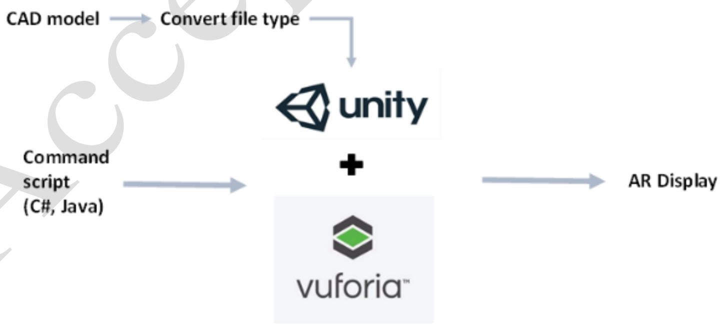


Figure 16: The workflow of AR realization using Vuforia in Unity.

The database enables the marker-based AR by activating “ARCamera” and “ImageTarget” prefabs to recognize and track objects for data registration with a built-in algorithm, which can provide the coordinate transformation of camera pose in a real-time manner. Once the data has been loaded, the user can activate the

"Image Target Behavior" of the "ImageTarget" prefab by setting the dataset and image target. After the setting is finished, the augmented view can be visualized through the display while the marker is being captured by the camera. Figure 17 shows the AR scene with generated CAD models superimposed.

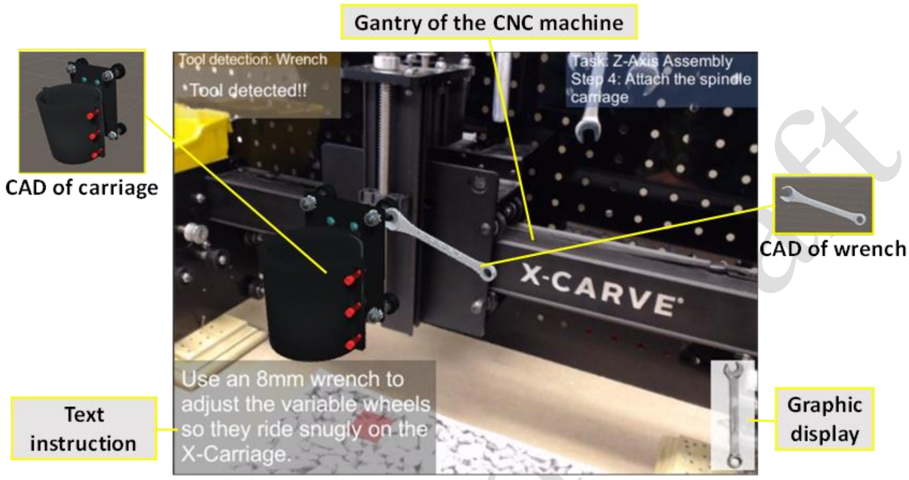


Figure 17: An assembly scene runs in real time with AR instructions. Multiple types of instructions are rendered through a display including texts, graphics, and 3D animations.

1.4.4 *Hand interaction*

A Leap Motion Controller is applied in this study to realize simple hand interactions with virtual objects. Leap Motion SDK is used to return the spatial coordinates of the real hands and Vuforia is responsible for superimposing graphic hands onto the real hands in an AR scene. To interact with virtual objects, the scripted interaction behavior and physics features for graphic hands and objects are required to simulate the real-world activities as if the user is interacting with the physical objects. Figure 18 shows the interaction between real hands and virtual objects with various geometries.

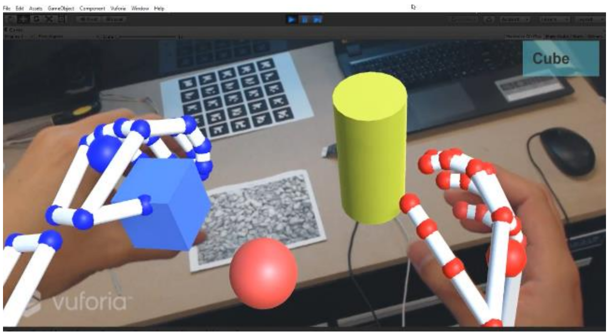


Figure 18: Hand interaction with virtual objects in an AR scene.

1.4.5 *Experiment and Evaluation*

To evaluate the effectiveness of the AR guidance, we have applied it in an experiment to instruct users to conduct an assembly task and its performance is compared with the traditional manual guidance. Figure 19 shows the overall experimental setup. There are 20 subjects recruited completing the task.

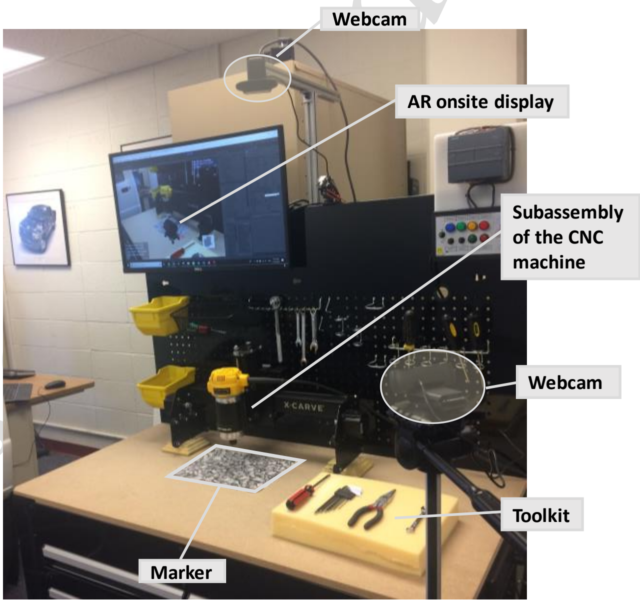


Figure 19: The workstation setup for the experiment.

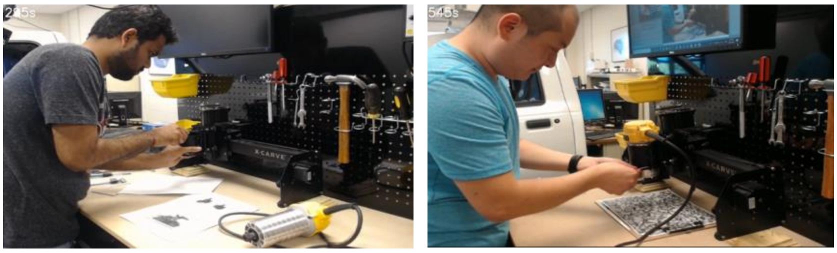


Figure 20: A comparison of two subjects performing the experiment with two different methods: (left) manual and (right) AR.

The 20 subjects are divided into two groups with AR and manual instructions provided, respectively. During the experiment, each subject is asked to perform the assembly task by following the instructions step by step; see Fig. 20. To assess the performance, the completion time and number of errors are recorded throughout the experiment. The performance comparison is shown in Figure 21; by using AR guidance, the completion time and number of errors show 33.2% and 32.4% of reduction, respectively. The considerable improvement demonstrates the great potential of applying AR technology to industries for manufacturing assembly training.

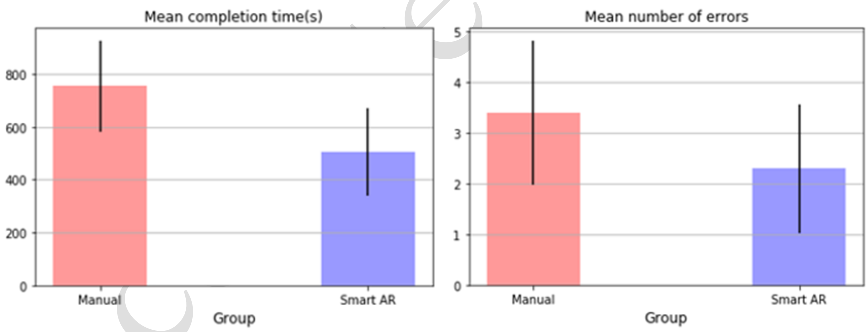


Figure 21: The comparison between manual and AR guidance: (left) completion time and (right) number of errors.

1.5 Technology Limitations and Research Needs

This section discusses the limitations and challenges of current VR/AR and MAS technologies and future research needs towards MAS realism improvement, worker behavior understanding, and sharing and collaborative MAS.

1.5.1 *MAS realism improvement*

To further improve the realism of MAS in VR/AR environment, research and development efforts are needed to advance VR/AR technologies aimed at accomplishing the following objectives:

(1) High-fidelity and low-latency graphic visual interfaces need to be developed. For example, for head-mounted VR/AR systems, the optical system design needs to be advanced [29] for increased display resolution, update rate, and field of view, and for reduced size and weight of the headset.

(2) To enhance the visual interface for better immersive VR/AR experience, the following efforts are needed: (a) Advance the technique of 3D auditory feedback; (b) Develop multichannel haptic devices to provide users with richer touch feedback and allow them to feel the surface texture, shape, softness/hardness, and temperature of an object; (c) Further develop locomotion interface [56, 71] to provide realistic walking/running experience in the virtual environment; and (d) Explore the senses of smell and taste to augment the realism of MAS applications.

(3) To realize better environment perception for AR systems, marker-less tracking methods need to be improved. The SLAM technologies have provided promising solutions for environment perception in AR. They need to be further studied for improved efficiency and robustness. Object detection and recognition techniques also need to be further developed for more advanced environment awareness.

(4) More accurate, efficient, robust, and low-cost human pose estimation approaches need to be investigated. Multi-modal motion tracking devices, advanced data fusion techniques, and deep learning methods can be exploited in this study. Motion sickness [44, 55] is another challenging issue affecting the user's experience, which needs to be solved with more accurate and efficient motion tracking approaches.

(5) Currently most of the human-environment interactions are conducted with some input/output devices such as a 3D mouse or a controller. More natural ways such as voice, gaze, and gesture interaction [73] technologies need to be developed.

1.5.2 *Worker behavior understanding*

In a MAS task, understanding the worker's behavior can be used for quantification and evaluation of the worker's performance, as well as to provide onsite instructions in VR/AR [74]. Studies in the following aspects need to be conducted:

(1) Methods for real-time worker activity recognition need to be researched for understanding the worker's current assembly activity during a MAS task. Then the time taken for each assembly step can be analyzed for quantification and evaluation purposes.

(2) Besides activity, the worker's emotional states (e.g., stress, confusion and fatigue) should be considered in MAS, which can be estimated using sensors such as an Electroencephalography (EEG) headset, or through advanced facial recognition techniques [40].

(3) On-demand virtual guidance for MAS should be developed based on the worker's states (e.g., activity and emotional states) to improve the interaction efficiency with minimal guidance to the worker [105]. Also, methods for online assembly quality evaluation need to be developed.

1.5.3 *Sharing and collaborative MAS*

Due to the increasing complexities of assembly products and prevalence of global partnership in the design and manufacturing processes, sharing and collaborative MAS are needed in such contexts. It allows team members located in different geographical locations and time zones to share their knowledge and expertise and conduct cloud-based collaboration. Research opportunities in the area of sharing and collaborative MAS include the following:

(1) For MAS involving multiple users in the VR/AR environment, sharing the same virtualized/augmented world and digital contents requires more accurate, efficient and robust registration and tracking algorithms, in order to register multiple users to the same coordinate system precisely and keep synchronizing their shared contents promptly.

(2) The design interface and interaction in these situations will be more challenging because it involves not only interactions between users and digital contents, but also interactions between different users. How to enable users to have natural, effective distance collaborations in the VR/AR scenarios as they do in the real workplace is another challenge that needs to be addressed.

(3) To achieve simultaneous interfaces of VR/AR contents and concurrent interactions among collaborators in different geographical locations, advanced computing, networking, and communication architectures and methodologies, along with the necessary hardware and software, need to be developed and implemented.

1.6 Conclusion

This chapter focuses on utilizing Virtual Reality/Augmented Reality (VR/AR) technologies for assembly simulations in advanced manufacturing. First, some basic terminologies and concepts have been clarified in terms of VR, AR, and manufacturing assembly simulation (MAS). Then the state-of-the-art methodologies for developing MAS applications including modeling, sensing, and interaction that enable the VR/AR assembly simulations has been reviewed and discussed. In particular, the discussion has included how to acquire digital data from a real object and how to reconstruct a 3D model using the acquired data. This chapter also has presented different methods for AR tracking and human pose estimation. Moreover, human-computer interfaces for rendering and interaction, including visual, auditory and haptic interfaces, have been discussed. Further, this chapter has included some assembly application examples that incorporate VR/AR technologies for MAS and has demonstrated the potential of MAS systems for shortening the product design cycle, improving product quality, and enhancing worker skills. A hands-on project has been used in a case study to provide a practical guide to implementing a VR/AR assembly simulation application. Finally, the limitations and challenges of current VR/AR technologies and future research needs in terms of MAS realism improvement, worker behavior understanding, and sharing and collaborative MAS have been discussed.

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