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Teaching Manufacturing Assembly Processes Using Immersive Mixed Reality

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Abstract

Successful assembly processes positively impact the U.S. manufacturing sector's economy by optimizing the manufacturing system, lowering the production cost, and increasing the profitability for manufacturers, all of which enhance supply chain resilience and reinforce sustainability. Given the significance of the assembly process in manufacturing and its considerable impact on the U.S. economy, developing new instruction methods for teaching assembly practices in manufacturing is crucial. Educators and researchers have been developing new methods for teaching assembly processes to help develop a skilled workforce and prepare students to contribute to the future growth of the manufacturing sector. Many of the exciting methods currently employed in manufacturing education are pivoted on applied teaching, like project-based and competition-based learning and other applied hands-on teaching methods. Such methods have been proven effective; however, they exhibit limitations and challenges related to the cost of the equipment, lab space, regular maintenance, and other constraints related to securing a safe and friendly environment for students. In this context, we present the utilization of Mixed Reality (MR) technology as an immersive and engaging tool for teaching manufacturing assembly processes. MR is the forthcoming evolution of the human-machine interface in the real-virtual environment utilizing computers and wearables. The technology can be a practical pedagogic tool for teaching students' assembly practices in manufacturing education. For this reason, an interactive MR module on hydraulic gripper design and assembly has been developed as a proof-of-concept and incorporated into the MET:230 Fluid Power class, where a research study has been conducted to explore MR's effectiveness in teaching assembly processes. The module is developed and deployed in an MR setting using the Microsoft-driven platform Mixed Reality Tool Kit (MRTK) for Unity via HoloLens 2. It offers a wide range of capabilities and functionalities, such as introducing students to the grippers' basic components and subsystems, allowing them to visualize the internal structure of two different gripper designs, conduct assembly/disassembly procedures, and learn about the grippers' operation and mechanisms. The study findings reveal the effectiveness of the MR module in exposing students to assembly procedures in engaging lab activities. Before experiencing the lab, 55% of the students were unconfident about individual assembly, but 93% gained confidence after the lab. Additionally, 95% reported immersion and excitement during MR assembly. Such results show that the developed interactive MR module will serve as a perpetual mutable platform that can be readily adjusted to allow future add-ons to address future educational opportunities.

Keywords: Mixed Reality, Assembly, Manufacturing Education, Student Learning, Virtual Environments

1. Introduction

For over 200 years, the manufacturing sector has been the cornerstone of the U.S. economy, playing a significant role in fostering sustainable economic growth and competitiveness [1], [2]. This sector reinforces U.S. commercial innovation, offers high-wage employment, and is crucial in reducing the U.S. trade deficit [3], [4]. According to the U.S. Department of Defense, manufacturing processes contribute to 35% of the U.S. economic growth and account for 60% of U.S. foreign trade (exports) [5], [6]. Additionally, manufacturing operations are responsible for 55% of U.S. patents and 70% of research and development spending [5]. As of 2022, the manufacturing sector employs over 12.5 million people, providing rewarding, living wage jobs, all of which contribute significantly to the sector's resilience and impact on the overall U.S. economy [6].

The manufacturing processes involve a series of critical stages, from design and conceptualization to assembly and packaging, all contributing to the development of the final product [7]. Amidst all manufacturing phases, the assembly process plays a vital role in product development, given its intricate dynamics, highlighting the need for closer examination. Assembly is considered a critical phase in product manufacturing, constituting a considerable percentage of the total manufacturing and labor expenses [7], [8]. Effective assembly methods increase the quality of the entire product manufacturing process while cutting down on cost and time, thus contributing to the overall economic well-being of the U.S. [9]. Employing efficient assembly techniques enhances the overall performance of the manufacturing processes by achieving precision and consistency in assembling components, thus ensuring that the final product meets high-quality standards. Besides product quality, optimized assembly methods allow for resource savings, such as reduced material wastage and lower labor costs [10].

With all these benefits of assembly processes in manufacturing and their significant impact on the U.S. industrial strength and sustainability, it is crucial to investigate and develop new instruction methods for teaching assembly practices in manufacturing education [11]. To this end, educators have been exploring new methods for teaching assembly practices to prepare students to contribute to the future growth of the manufacturing sector, thus developing a skilled workforce. They have been looking for applied instruction techniques that can be simultaneously adopted in coordination with the existing traditional teaching techniques, i.e., lectures, sessions, and tutorials [12], [13]. Some educators have been adopting hands-on learning, like project-based learning (PBL) and competition-based learning (CBL), as essential pedagogical tools throughout the learning process [14]–[18]. For instance, in the study conducted in [19], the researchers employed PBL in undergraduate mechanical courses by developing a remotely controlled hydraulic demonstrator to expose students to the assembly procedure of mechanical, hydraulic, and electrical subsystems. The developed demonstrator served as a pedagogical simulator, demonstrating its effectiveness in instructing fundamental assembly strategies. Besides PBL and CPL, other groups of researchers have been utilizing web-based and virtual environment courseware [20]–[22]. Such courseware is a digitized material that uses computer-based hardware and software as educational tools. It is characterized by the flexibility of designing various engineering experiments, acquiring and analyzing data, and providing instantaneous feedback regarding the experiments' predictions and adjustments [23]. The individualistic nature of this courseware exposes students to the design process of an engineering product, from modeling and simulation to assembly and diagnosis [22].

All the introduced teaching approaches have proven effective in exposing students to assembly practices. However, they exhibit limitations and challenges related to the cost of the equipment, lab space, regular maintenance, and other constraints related to securing a safe and friendly environment for students [24], [25]. Such challenges are highly associated with the need to purchase and design hardware/software (mechanical components kits, toolkits, software subscriptions, electronic stuff), which might be expensive, complicated to manufacture, and thus inaccessible for some institutions. Besides the financial and technological hurdles, most of the adopted techniques are exclusive, limited, and still lack the potential to immerse students within industry-like settings [26].

Given these challenges, more research is required to investigate new teaching and instruction methodologies that enable exposing students to manufacturing assembly strategies while immersing them in industry-like settings. Therefore, this work is motivated by the need to explore new practical approaches to teach manufacturing assembly procedures. It presents the use of Mixed Reality (MR) technology, the state-of-the-art Digital Reality (DR), as an immersive, engaging tool for exposing students to assembly practices and concepts in manufacturing education, offering comprehensive learning outcomes. Integrating DR technologies, such as MR, into manufacturing education aims to achieve the following learning outcomes:

1- Improve the students' understanding of assembly processes/methods: MR simulations will provide students with immersive experiences, allowing them to visualize and interact with assembly procedures in a realistic environment.

2- Improve the students' problem-solving skills: MR applications will expose students to realistic assembly challenges and scenarios, reinforcing their critical thinking and problem-solving skills to overcome obstacles.

3- Expose students to real-world application of theoretical concepts: MR technology enables students to narrow the gap between theoretical knowledge and practical application by simulating real-world manufacturing environments.

4- Expose students to experimental learning at minimum cost: MR simulations will provide students with experiential learning opportunities, allowing them to actively engage with assembly tasks and learn through hands-on experience.

5- Enable collaborative learning and teamwork: MR applications can be designed in shared settings (as will be revealed in our future work) to facilitate collaborative learning experiences, allowing students to work in teams to solve assembly challenges.

All these learning outcomes will contribute to preparing students for industry roles, equipping them with the required skills to succeed in their future roles within the manufacturing industry.

The rest of this paper is organized as follows. Section 2 (Background) exhibits a comprehensive overview of DR technologies, their features, limitations, and applications in manufacturing education. It also compares the DR technologies, highlighting the optimal state-of-the-art technology. Section 3 (Interactive MR Module for Teaching Assembly) introduces our proposed methodology, i.e., MR teaching modules. It presents the module development, setup, capabilities, and functionalities. Section 4 (Research Study) presents the conducted study, illustrating the adopted experimental design and data collection tools. Section 5 (Results and Analysis) provides a thorough discussion of the resulting outcomes. Finally, in Section 6 (Conclusions), the paper summarizes the essential findings and insights from the work.

2. Background

With all the rapid technological advancements, DR technologies, i.e., the use of high-tech visualization media, are adequate instruction tools utilized in manufacturing education to introduce students to design optimization and assembly processes [27], [28]. DR technologies enable manufacturing educators to design and develop interactive pedagogical modules to share digital representations of certain physical assets, processes, or systems through a virtual platform known as the virtual environment [29]–[31]. DR involves virtual reality (VR), augmented reality (AR), MR, and all digital technologies that come within, as shown in Figure 1.

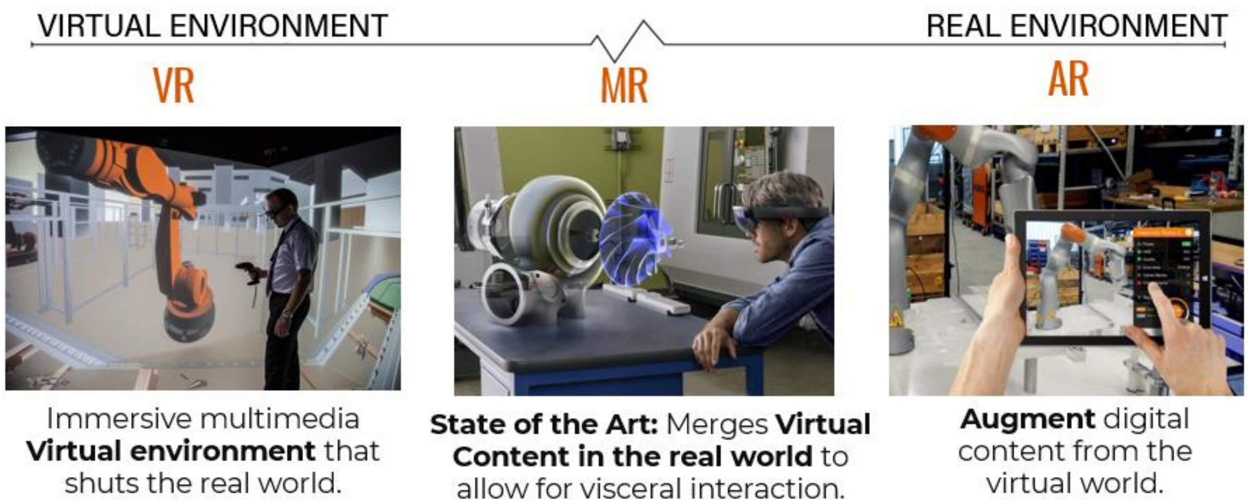

Figure 1. DR Technologies from Virtual to Real Settings

VR is an immersive computer-generated simulation that can achieve a sense of presence and immersion by creating a realistic, visceral experience that tricks the user's senses into thinking of being immersed [32], [33]. This immersive multimedia is experienced using smart-wear techs like headsets, skin electronics, and many other wearable devices, allowing users to interact with life-like models in a safe virtual environment [20]. Given its features, VR has been widely employed in manufacturing education as an effective teaching tool for introducing students to assembly strategies in a virtual environment mimicking industry-like setting [34], [35]. For instance, the work in [35] presents a VR application focusing on sustainability in Industry 4.0 manufacturing developed for engineering education. It showcases the impact of VR training programs on enhancing students' knowledge of sustainable practices and practical skills. The work shows a case study emphasizing engineering education's role in promoting sustainability in Industry 4.0. However, despite all the implemented efforts in engineering education with VR and VR's immersive multimedia features, VR technology has some considerable technical problems related to real-time fidelity, image integration, and motion sickness [36], [37]. The real-time fidelity of virtual environments is highly correlated with the robustness of the digital representations in the VR setting. Also, VR is still incapable of recognizing the resemblance between images and the degree of image distortion [37]. Besides the technical issues, experiencing immersive VR environments for a long time causes motion sickness/discomfort, i.e., headaches, nausea, eyestrain, and disorientation [38], [39]. Hence, to ensure students' safety and enhance their educational experiences, some educators have been exploring alternative DR technologies, such as AR [40].

While VR disconnects the user from reality, AR introduces a new practice of visualization, enabling interaction with real surroundings by superimposing rendered visuals [41]. AR allows overlaying digital objects in the real world via smart devices, like phones, screens, or displays, which are widely available and affordable [42]. Consequently, AR is more accessible to educators and researchers and allows for addressing the adverse effects associated with VR, like headaches, eyestrain, etc. AR has been utilized by many educators in manufacturing, specifically industrial engineering [43]–[45]. For instance, the work in [43] presents the development of an AR application installed on Android phones and tablets. The application has multiple options to enable students to augment 3D assets for a globe valve model by scanning QR codes/images and assembling the valve by interacting with virtual UIs through the phone/tablet screen. Despite the significance of the AR application and its applicability to allow students to visualize 3D assets for mechanical systems, it lacks eye/hand tracking, spatial awareness, and advanced spatial interactions. Therefore, while AR offers accessibility benefits, it has limited features and functionalities compared to VR. These limitations are related to the level of immersive experiences and interactive capabilities, potentially posing challenges for educators in achieving comprehensive learning outcomes in manufacturing education.

An extension to AR is MR, also known as the state-of-the-art DR technology. MR represents the forthcoming evolution of the human-machine interface in the real-virtual environment utilizing computers and wearables [46]. This advanced technology combines the features of VR and AR, addressing issues associated with each [47]. It permits merging the substantial environment with the predesigned virtual world through a smooth human-computer, providing the user with a hybrid experience that blends the real world with virtual objects [48]. MR allows for providing different types of feedback in real-time, like audio, visual, and haptic feedback, extending users with seamless access and a degree of controllability through interacting with UI controls, thus enhancing the user’s experience. Besides real-time feedback, MR utilizes high-tech visualization packages that allow for improving the quality of the rendered image without affecting the real-time feedback. Also, it allows running simulations that examine the complexity of intricate systems, thus understanding their corresponding physical phenomenon. Unlike VR, which can expose users to severe motion sickness, MR can be readily experienced through holographic devices, i.e., head-mounted see-through displays and headsets, resolving discomfort issues. These holographic headsets comprise translucent glasses that allow users to navigate physical reality with immersive holograms while interacting with virtual assets, thus relieving the potential for motion sickness [49].

With these features, MR technology aims to solve VR-related issues, like image quality, real-time fidelity, motion sickness, etc., while maintaining the required level of immersive experience and interaction, increasing its usage in many applications. Thus, many researchers have started to employ MR technology in manufacturing education [50], [51]. The work presented in [51] proposes integrating VR and AR by combining a virtual assembly environment with an AR application. However, the adopted approach utilizes a hybrid tracking system to synchronize virtual and real hands, lacking the advanced holographic features of MR technology. Although the MR system integrates AR and VR using webcams, gloves, and display monitors, it does not leverage state-of-the-art holographic capabilities, such as those offered by holographic glasses, to augment interactive virtual assets in the real world. Furthermore, the application falls short of incorporating advanced MR functionalities such as spatial awareness, eye/hand tracking, and user UI controls compatible with HoloLens 2 articulated hand input.

To this end, our current work aims to examine the effect of utilizing holographic MR technology as an instruction tool in manufacturing education to introduce students to assembly procedures and practices. Thus, an interactive hydraulic gripper assembly module has been designed and developed to introduce students to the assembly concepts/ stages of two different types of grippers and their associated mechanisms. The module is then incorporated into Mechanical Engineering Technology MET:230 Fluid Power course laboratories. A research study has been conducted to explore MR's effectiveness in teaching assembly processes, where the module has been experienced by 102 undergraduate students registered in the course.

3. Interactive MR Module for Teaching Assembly

The interactive MR module is designed for undergraduate-level students using the Microsoft-driven platform Mixed Reality Tool Kit (MRTK) for Unity via HoloLens 2. It introduces students to two types of hydraulic grippers (light-duty and heavy-duty), their components, subsystems, assembly procedures, and operations. The following two subsections discuss the module’s development/setup and capabilities.

3.1 Module Development

Figure 2 shows a diagram illustrating the module development, highlighting the different software used to set up the MR setting and develop the interactive gripper assembly module. Throughout the MR module development, Unity 2021.3.16, a cross-platform game engine provided by Unity Technologies [52], is utilized as the centered software to create and design interactive MR experiences within a spatial immersive environment. To import and interact with the highly-coupled gripper 3D models and their associated physics/simulations in Unity, the CAD models are optimized and refined using SolidWorks. Then, the models are converted from an STL file into FBX file, supported by Unity, through Blender software, an open-source 3D computer graphics [53]. Besides using Blender as a window file converter, this software assisted in optimizing the grippers’ animations and motion simulations to be readily imported as FBX assets into Unity.

Additionally, Mixamo, a 3D character animation platform, is utilized to incorporate 3D animated characters with audio feedback. These characters function as virtual agents (avatars), providing instructions and guiding the students while navigating and interacting in the MR setting. In addition to preparing and importing the necessary 3D models, it is required to set up the Mixed Reality playspace by downloading the (Mixed Reality Feature Tool Kit) Application [54]. This application allows adding, importing, and updating the basic MRTK packages (MRTK Foundations, MRTK Extensions, MRTK Test Utilities, and MRTK Tools) and other required packages to the Unity project.

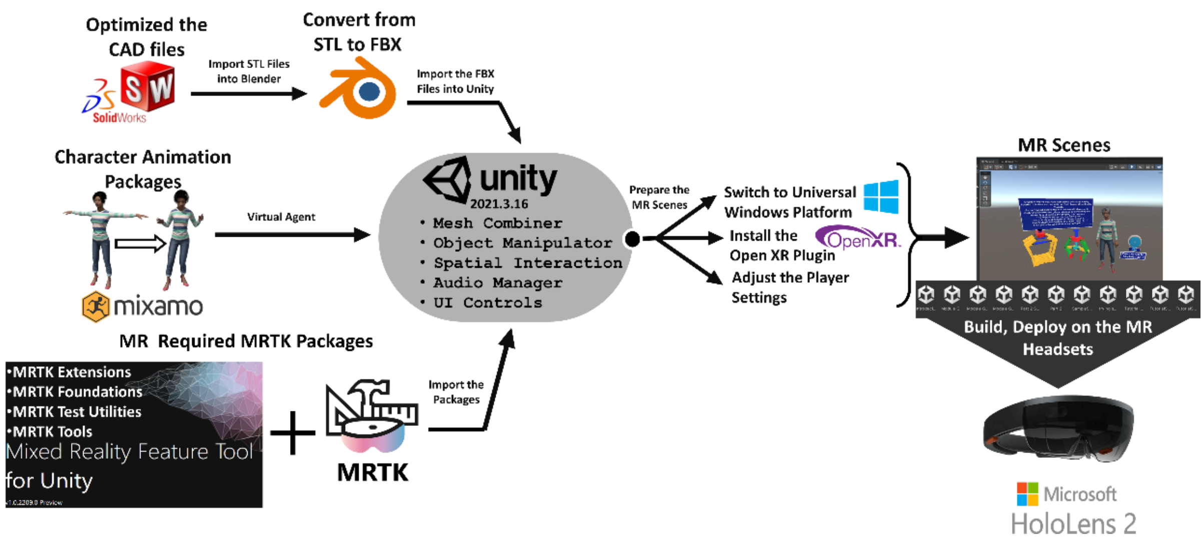

Figure 2. MR Module Setup and Design

After importing the necessary CAD files, avatar models, and MRTK packages, the module is divided into multiple interactable scenes connected in a predefined sequence through user-friendly UI controls that allow users to seamlessly navigate between scenes. Each scene concentrates on specific activities/tasks associated with the module. For instance, one scene focuses on exposing students to MR and its technological features and functionalities through a short tutorial. Another scene is pivoted on providing a brief introduction to the lab and the associated grippers. Other scenes focus on exposing students to the grippers' assembly, operations, and mechanism. For each scene, Unity scripts (object manipulator, mesh combiner, assembly, spatial interaction, etc.) are created and compiled using `(UnityEngine)`, `(UnityEngine.Events)`, `(Microsoft.MixedReality.Toolkit.UI)`, `(HoloToolKit.Unity.Buttons)`, etc., to allow for various types of interactions, like grabbable/grabber interchange and near and far object manipulation. The scripts also allow spatial awareness, eye/hand tracking, and user UI controls supporting HoloLens 2 articulated hand input. This adopted procedure enables the creation of an interactable MR setting to visualize and interact with the gripper models, like touching, manipulating, conducting assemblies/disassemblies, etc. Finally, the module is built and deployed on the HoloLens 2 headset, the holographic device designed and manufactured by Microsoft, to be tested among research members before being incorporated into the MET: 230 course.

3.2 Module Capabilities

The MR module comprises two main sections: (1) MR Tutorial and (2) Hydraulic Grippers Assembly Lab. Each section consists of two to three activities with multiple capabilities and functionalities.

3.2.1 MR Tutorial

The MR tutorial aims to expose students to MR technology, its features, dimensions, and constraints and introduce them to the different types of interactions and UI controls within an MR setting. It allows students to get familiar with this new technology by teaching them the fundamental spatial interactions they will experience throughout the hydraulic gripper assembly lab. This tutorial comprises two main activities (Activity 1: Object Manipulation and Activity 2: Assembly and Hand Interaction), shown in Figure 3.

Figure 3. Activities of the Section 1 of the MR Module

Activity 1 is designed to expose students to different object manipulation techniques within an MR setting. It teaches students basic manipulation and touching techniques, like near and far manipulations, allowing them to manipulate (point, rotate, scale) virtual assets of different sizes from various distances using their fingers. In contrast, **activity 2** exposes students to other hand interaction techniques, like object grabbing, snapping, and assembly.

3.2.2 Hydraulic Gripper Assembly Lab

The hydraulic gripper assembly lab is experienced by the students right after the MR tutorial. This MR lab exposes the students to the two types of grippers (light duty and heavy duty), their components, assembly procedures, and associated mechanisms through three consecutive activities on each gripper (Activity 1: Components, Activity 2: Assembly, Activity 3: Motion Simulation), illustrated in Figure 4.

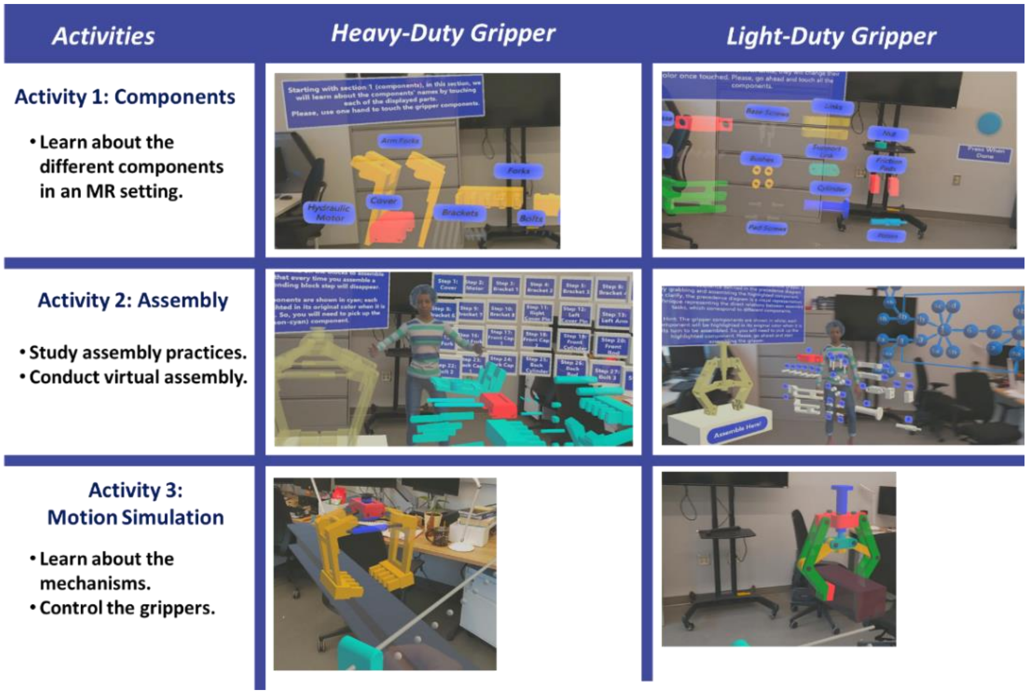

Figure 4. Activities of the Section 2 of the MR Module

Activity 1 is designed to introduce students to the gripper's sub-systems (hydraulic and mechanical) and their associated parts in MR settings. This activity involves hand tracking with near manipulation techniques introduced through the tutorial section to enable learners to touch and interact virtually with the gripper's components. It helps them identify and categorize the gripper pieces into hydraulic and mechanical sets. Additionally, the activity provides detailed technical information and specifications for the components immediately after they are touched, as shown in Figure 5. As shown in the figure, visual indications, such as color changes, are incorporated throughout the activity to facilitate user interaction with the digital representations of the gripper components. This approach enhances the user's experience by offering immediate feedback; for instance, when a component is touched, its color shifts from white/cyan to original color, providing users with prompt information about their interaction with the component.

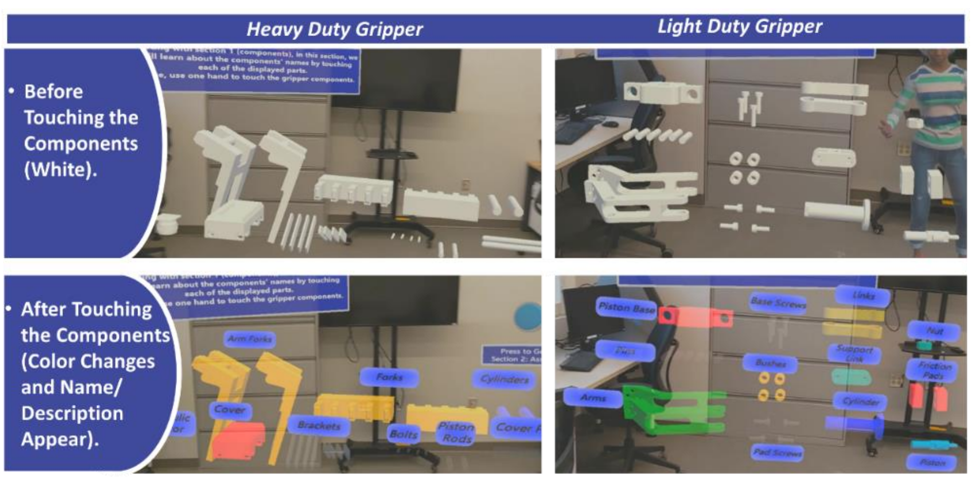

Figure 5. Activity 1 (Components)

Activity 2 serves as the core of the MR module, as it focuses on exposing students to assembly procedures. It enables them to assemble both grippers using different techniques following a predefined sequence (see Figure 6).

Throughout this activity, students will learn to interpret various assembly graphical diagrams, including the precedence diagram, a visual representation method. This visual representation illustrates the direct connections among assembly tasks, each corresponding to distinct components. Besides being a graphical tool, this diagram provides valuable insights into critical paths and potential design gaps. This comprehensive tool is essential in manufacturing education, helping assembly teams make critical decisions, optimize resource allocation, and ensure a well-coordinated effort in component assembly [47].

Before introducing the precedence diagram, students must first assemble the heavy-duty gripper using the regular assembly technique, following the steps on the blue blocks. Then, they are introduced to the precedence diagram, where they are asked to adopt this technique for assembling the light-duty gripper. As shown in the figure, students must grab the correct component, manipulate its orientation/configuration, and assemble it in its proper spot on the transparent gripper structure based on the sought-after assembly procedure.

Hints are also provided through visual aids, such as unique colors for components and highlighting those to be assembled. Furthermore, after three incorrect attempts, the corresponding spot for the gripper component will be highlighted differently on the gripper's structure to assist in correct placement.

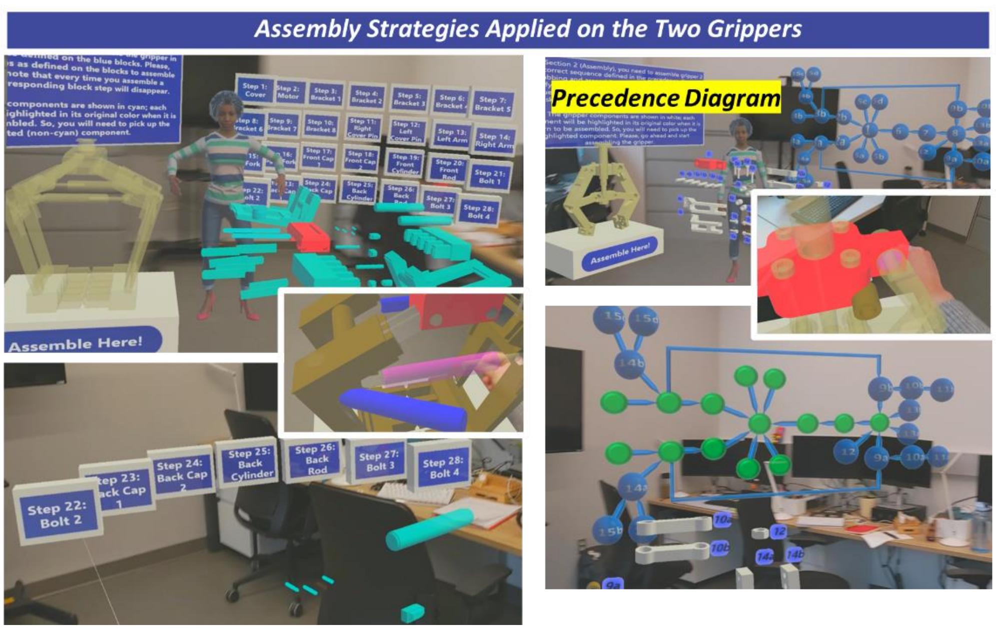

Figure 6. Activity 2 (Assembly)

The last activity, **activity 3**, enables the students to study and inspect the associated mechanisms of both grippers right after assembling the grippers by interacting with virtual UI controls, like virtual slides and joysticks. Throughout this activity, students must employ the near and far manipulation techniques learned in the tutorial section to simulate the motion of the mechanical and hydraulic subsystems, as shown in Figure 7. By utilizing these virtual UI controls, students can explore the complex mechanisms of the grippers in a controlled and safe environment, exposing them to the associated functions. Besides visualizing and studying the system's mechanism, this activity introduces students to various safety protocols that must be observed when operating hydraulic systems. To this end, activity 3 offers a practical and effective approach to mechanism testing after assembly, ensuring that students are well-prepared to handle the equipment when they enter the workforce.

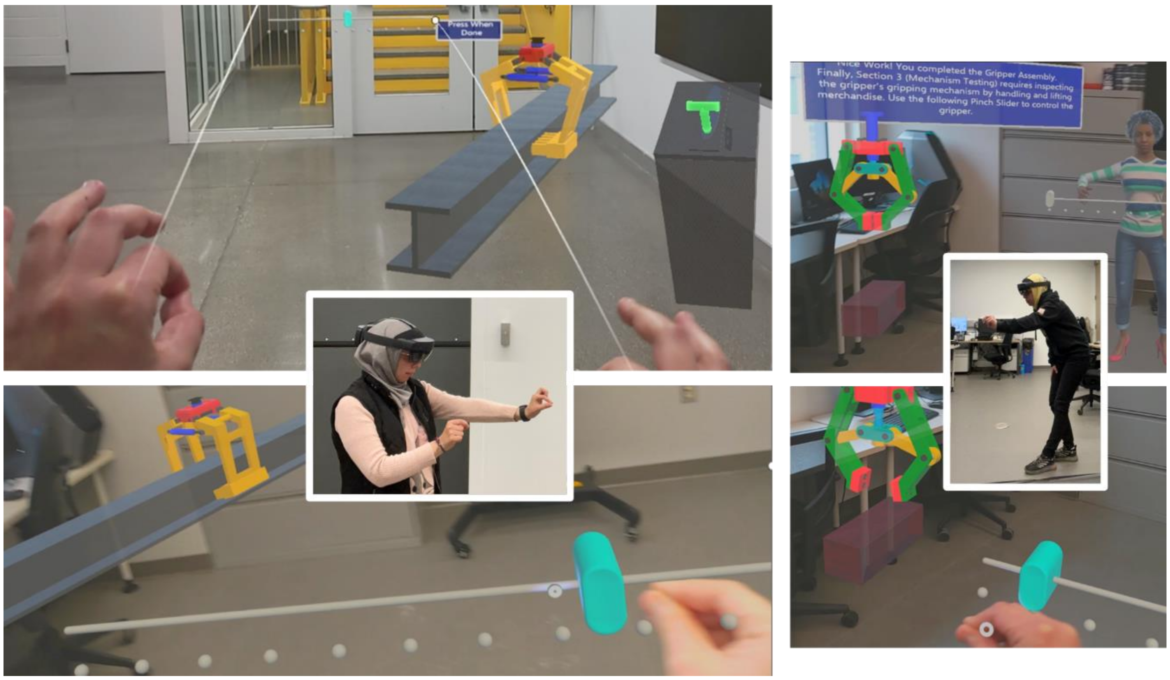

Figure 7. Activity 3 (Motion Simulation)

4. Research Study

Following the development of the MR module and the assessment of its technical features within the research and laboratory team, the module has been integrated into the MET:230 Fluid Power course laboratories. A research study has been generated with 102 students (comprising eight females and 94 males) enrolled in the MET:230 course, where an institutional review board (IRB) application was filled out and submitted. Surveys were designed and managed to assess the MR module’s impact on teaching assembly processes. All students engaged with the interactive MR module and completed the required surveys during one of their course lab sessions. The following subsections introduce the designed surveys and the adopted experimental design.

4.1 Surveys

Surveys have been designed for this research study to examine the effectiveness of employing MR as a teaching tool in manufacturing education. The surveys consist of four pre-and-post Semantic differential questions and four self-reflection Likert-scale questions, shown in Table 1. The data acquired by the Semantic differential questions are based on the 1 to 5 bipolar scale rating (5: Very Certain, 4: Certain, 3: Moderate, 2: Certain, and 1: Very Uncertain). Also, the data collected by the Likert scale questions are based on a 5-point bipolar scale (5: Strongly Agree, 4: Agree, 3: Neither Nor, 2: Disagree, and 1: Strongly Disagree).

Table 1. The Designed Survey Questions

#	Question		Anchors of the Scale
Pre-and-Post Semantic Differential Questions			
	Pre	**Post**	1 = Very Uncertain, 5 = Very Certain
Q1	How do you rate your background knowledge of Hydraulic Gripper Design/mechanism?	After conducting today's lab, how do you rate your confidence and understanding regarding gripper designs/mechanisms?	
Q2	How do you rate your knowledge regarding the grippers' utilized mechanical/hydraulic components?	After conducting today's lab, how do you rate your knowledge regarding mechanical/hydraulic components?	
Q3	How do you rate your understanding of each of the grippers' operations?	How do you rate your understanding of the grippers' operation after conducting the MR lab? The MR simulation helped me readily visualize and understand the operation/mechanism of each of the gripper designs.	
Q4	How do you rate your experience with hands-on experience?	How much do you feel that the assembly module in the MR simulation lab gave you (hands-on)?	
Self-Reflection Likert scale Questions			
Q5	The MR module helped me understand the assembly of hydraulic grippers.		1 = Strongly Disagree, 5 = Strongly Agree
Q6	The visual aids (color/texture change) in the MR module guided me throughout the assembly procedure.		
Q7	The interactive MR module made the assembly task more entertaining and engaging.		
Q8	Besides the visual aids, the display of the utilized assembly diagrams (precedence diagram) in an MR setting helped complete the assembly faster.		

The pre-and post-questions aim to assess the improvement of the students' learning by comparing their understanding of the sought-after concepts before and after experiencing the module. For instance, questions Q1 to Q4 measure the students' confidence in their understanding of the hydraulic system assembly and operation. In contrast, the self-reflection questions Q5 to Q8 measure the students' internal beliefs and attitudes toward the MR modules, i.e., employing MR technology for teaching assembly concepts and practices. They provide a deeper insight into the students' perspectives on the MR module, enabling a comprehensive analysis of their experiences.

4.2 Experimental Design

The research study is administrated as follows. MET:230 class involved 102 students divided into seven sections, each comprising 14 to 15 students. To accommodate the number of students, the 15 students per section have been divided into five groups, each comprising three students. This resulted in 35 groups over the seven sections, each with three students. All 102 students completed the pre-survey before experiencing the module and then conducted the MR lab.

Six MR headsets have been purchased. The time to complete the MR module ranges from 20 to 30 minutes, and the overall session time is two hours. Subsequently, given the number of MR headsets and lab time, the study was conducted in 35 experiments over the seven sections in two consecutive weeks (17 experiments in week 1 and 18 experiments in week 2). Consequently, in each of the seven sections, two to three experiments are conducted consecutively every week. Each experiment required three MR headsets (the other three on charge) for the three students who experienced the MR module simultaneously but independently, i.e., each student in their scene. Figure 8 shows three students per group experiencing the MR module within one of the sections.

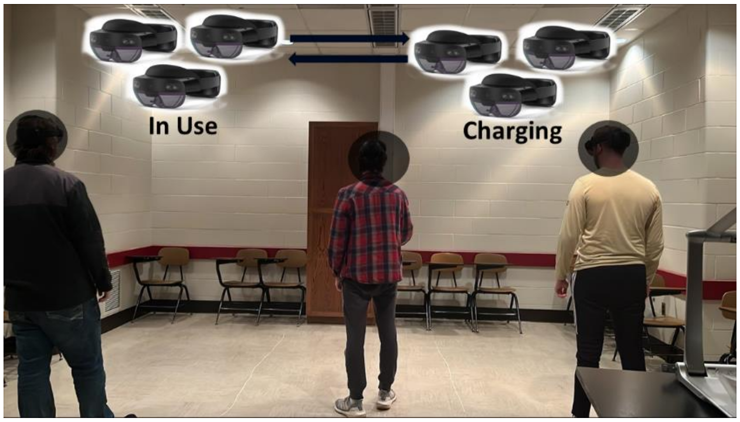

Figure 8. Three students per section experiencing the MR module

After the three students experienced the MR module, they were guided by their lab instructor to complete the post-survey. While these students fill the post-survey, the other three students in the following group are asked to complete the MR module tasks. This procedure has been consistently applied across all the other groups in the other sections, ensuring the participation of all students and facilitating study management and data collection. Then, two weeks after all the students experience the MR module, students are asked to complete the self-reflection survey. Out of the 102 students, 90 completed the self-reflection survey.

Therefore, the collected data comprised 102 responses on the pre-and-post surveys and 90 responses on the self-reflection survey. All surveys have been managed through BrightSpace, an online course management platform. After completing the surveys on BrightSpace, unique identifiers were assigned so that the students’ names were no longer included in the data. This allowed for maintaining the confidentiality of time-series data.

5. Results and Analysis

After acquiring the data, the students’ responses to the Semantic differential and Likert scale questions are analyzed using descriptive statistical methods, i.e., mean and standard deviation computations. The results are reported and discussed in the following subsections.

5.1 Pre-and-Post Survey Results: Semantic Differential (102 Response)

The findings of the descriptive analysis of the pre-and-post semantic differential questions are reported in Table 2 and Figure 9. The results show that the students’ responses to questions Q1 to Q3 pre the MR lab exhibited low mean values (between 2.6 and 3), indicating that the majority of the students’ responses to these questions range between “Uncertain” and “Moderate”. However, the responses to these questions after the MR lab revealed a significant increase in the mean values (above 4), showing a considerable improvement in the responses, ranging between “Certain” and “Very Certain”. For instance, the students’ responses on Q1 pre-and-post the MR lab are ***(M = 2.647, SD = 0.218)*** and ***(M = 4.431, SD = 0.391)***, respectively, indicating the significant improvement in the students' knowledge of the hydraulic grippers after experiencing the MR module. This shows that the MR module increased students' confidence in comprehending the design and assembly procedure of the grippers. Similarly, the students' responses to Q2 before and after experiencing the MR lab are ***(M = 2.912, SD = 0.246)*** and ***(M = 4.216, SD = 0.37)***, respectively, revealing that the students' gained a significant understanding of the grippers' components/material after visualizing the 3D representations of the grippers within an MR setting. Besides Q1 and Q2, the results of Q3 reveal a significant improvement in the students' understanding of the fundamental concepts of the grippers' operation. Q3 results improved from ***(M = 2.971, SD = 0.252)*** to ***(M = 4.618, SD = 0.408)*** after conducting the MR lab.

Table 2. Means and Standard Deviations for Pre-and-Post Questions

Questions	*Minimum "Very Uncertain"*	*Maximum "Very Certain"*	*M (Mean)*		*SD (Standard Deviation)*	
			Pre-MR	***Post-MR***	***Pre-MR***	***Post-MR***
Q1	1	5	2.647	4.431	0.218	0.391
Q2	1	5	2.912	4.216	0.246	0.37
Q3	1	5	2.971	4.618	0.252	0.408
Q4	1	5	4.01	4.382	0.353	0.389

These findings are supported in Figure 9, represented in blue, orange, and grey bars. For Q1 pre-MR (represented by the blue bar), the majority of the students, i.e., 56 out of the 102 (55%), reported "Moderate", 39 students (38%) reported "Very Uncertain" and "Certain", the remaining 17% responded "Very Certain" and "Certain". However, after the MR lab, the students' responses to Q1 significantly improved. 95 out of the 102 students (93%) reported "Very Certain" and "Certain", while the rest (7%) reported "Moderate", i.e., nobody reported "Very Uncertain" or "Uncertain". Besides Q1, the responses to Q2 and Q3 exhibit very close results. Before the MR lab, 54 out of the 102 students' responses (53%) were "Moderate" to both Q2 and Q3, around 26% of the students' responses were divided between "Very Uncertain" and "Certain", and the rest (around 27%) were "Very Certain" and "Certain". On the other hand, after conducting the MR lab, 88 out of the 102 responses to Q2 (86%) and 101 out of the 102 responses to Q3 (99%) were divided between "Very Certain" and "Certain".

Conversely, the results of Q4 did not show major improvement compared to Q1, Q2, and Q3 (see Table 2 and Figure 9). Students' responses to Q4 pre-and-post the MR lab are ***(M = 4.01, SD = 0.353)*** and ***(M = 4.382, SD = 0.389)***, respectively. The results of Q4 are also supported in the graphical representation in the yellow bars in Figure 9, revealing that most of the responses (more than 75%) before and after the MR are between "Very Certain" and "Certain".

These findings align with the learning outcomes and nature of MET courses, which heavily focus on hands-on activities, resulting in high hands-on skills among students. However, the data also indicate that the MR module had a limited impact on enhancing hands-on skills compared to fundamental concepts and principles. These findings call for the need to refine specific aspects of the module when hands-on training is a goal. Integrating advanced haptic technologies is one of the recommendations for targeting hands-on labs, as they allow hands-on learning to be addressed more effectively.

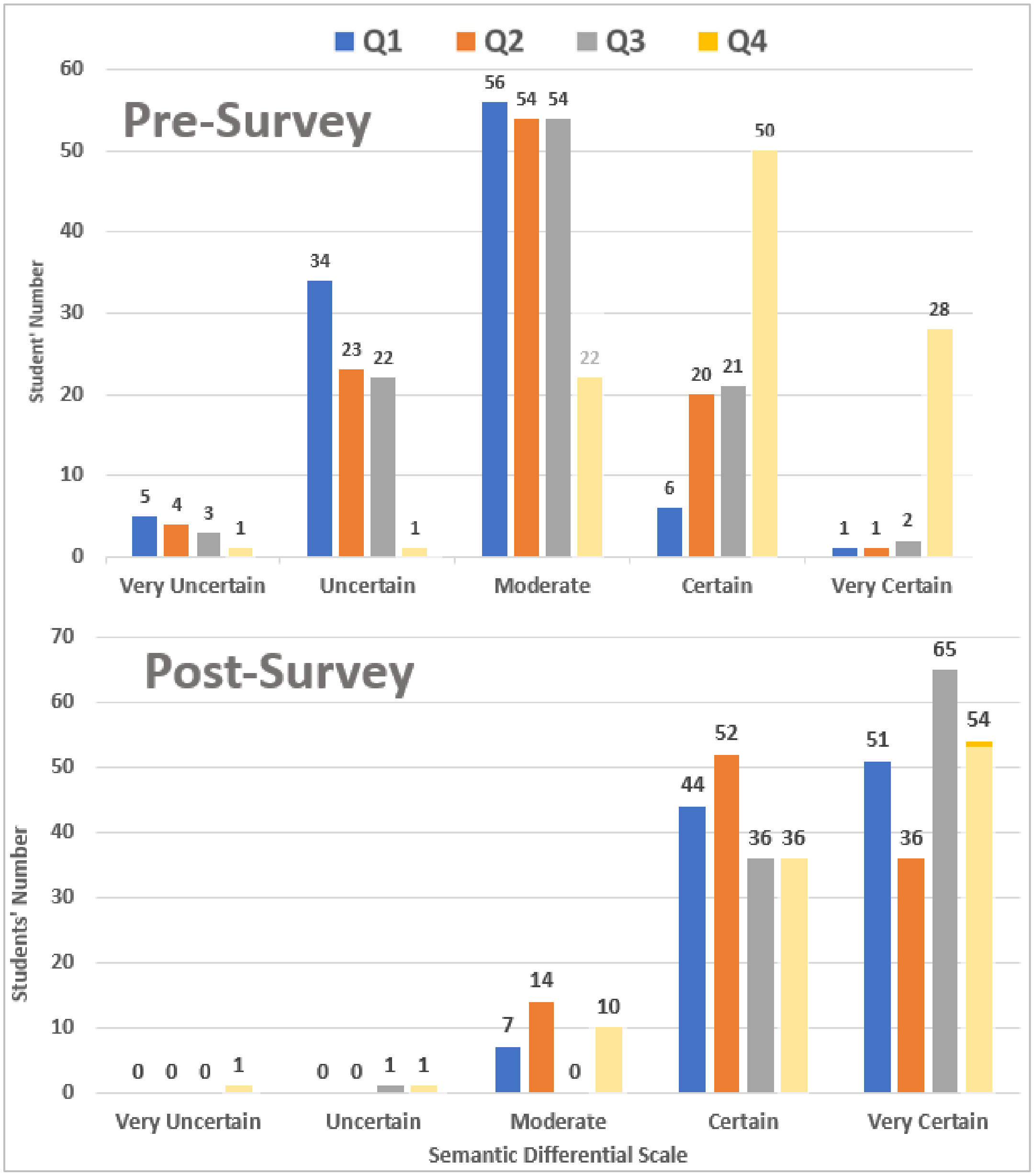

Figure 9. Statistical diagram illustrating the data collected from the participants' responses to the pre-and-post survey questions.

5.2 Self-Reflection Survey Results: Likert Scale (90 Response)

As mentioned, 90 of the 102 students completed the self-reflection survey questions. The outcomes of the descriptive analysis of the self-reflection Likert scale questions are reported in Table 3 and Figure 10. The results show that Q6 and Q7 got the highest mean values ***(M = 4.47, SD = 0.421)***, indicating that the students' responses to these two questions ranged from "Agree" to "Strongly Agree". This shows that the visual features of the MR module and the interactive augmented 3D representations positively impacted teaching assembly practices. Students were engaged and immersed while learning about assembly procedures, finding learning entertaining and exciting. These results are supported in Figure 10, represented in the orange and grey bars. The figure shows that around 85 out of the 90 responses (94%) on Q6 and Q7 are divided between "Agree" and "Strongly Agree", around 5% are "Neither Nor", and the rest (1%) are "Disagree", showing that the majority of the students benefited from the MR module's capabilities and features and enjoyed learning assembly through MR.

Table 3. Means and Standard Deviations for Self-Reflection Questions

Questions	*Minimum "Strongly Disagree"*	*Maximum "Strongly Agree"*	*M (Mean)*	*SD (Standard Deviation)*
Q5	1	5	4.367	0.410
Q6	1	5	4.478	0.421
Q7	1	5	4.467	0.421
Q8	1	5	4.211	0.398

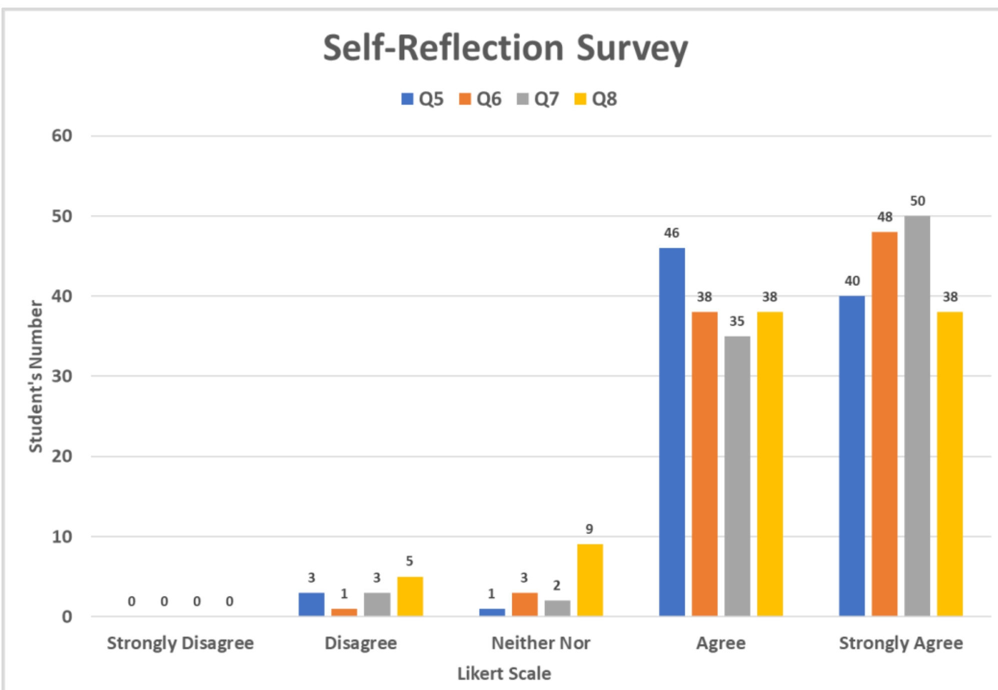

Figure 10. Statistical diagram illustrating the data collected from the participants' responses to the self-reflection questions.

Also, Q5 exhibited a relatively high mean and low standard deviation ***(M = 4.367, SD = 0.410)***, indicating that the majority of the students' responses, up to 96%, as reported in the blue bar in Figure 10, are divided between "Agree" and "Strongly Agree". So, more than 90% of the students achieved the assembly learning outcome after completing the MR lab. Few studnets (3%) reported "Disagree", indicating a preference against DR teaching methods due to the diversity in students' learning styles. This result reveals that such new teaching techniques can not fully replace the traditional teaching techniques but can be effectively employed in the incoordination of these standard teaching methods.

Finally, the results of Q8, which aims to explore the students' attitudes toward learning about specific assembly strategies, like the precedence diagram, also got high mean values ***(M = 4.211, SD = 0.398).*** As shown in Figure 10 (yellow bars), 76 out of the 90 students (84%) showed positive responses, "Agree" and "Strongly Agree". This indicates that the integration of visuals and animations effectively facilitated the students' understanding of the precedence diagram. Students showed effective performance while generating the assembly relying on this diagram, knowing their unfamiliarity with this strategy.

6. Conclusions and Future Work

This work is motivated by the need to explore and test innovative digital instructive methods, like MR modules, for teaching assembly procedures, given the significance of manufacturing assembly practices and their impact on the U.S. economy. Throughout this work, an interactive MR module on hydraulic grippers' assembly and operation has been designed and developed as a proof-of-concept to achieve some of the assembly learning outcomes. A research study has been conducted to examine the effect of this MR on teaching assembly and explore the effectiveness of integrating MR technology into manufacturing education. The module has been incorporated into the MET: 230 Fluid Power course and experienced by 102 students enrolled in the course. Pre-and-post and self-reflection surveys have been designed and completed by the students to examine the improvement in their understanding and test their attitudes toward the MR technology. The final outcomes revealed a significant improvement in the students' knowledge of the hydraulic grippers assembly after experiencing the MR module. Before generating the lab, around 55% of the students reported their lack of confidence toward conducting the assembly individually; however, after experiencing the lab, 93% of the students became confident about their understanding. Also, up to 95% of the students were fully immersed and reported excitement and enjoyment while assembling the gripper in an MR setting. A minimal percentage, around 3%, expressed a negative preference for using DR technologies for teaching. This result reveals that these new teaching techniques can not fully replace traditional teaching methods, but they can be integrated with standard teaching methods to address the students' diverse learning styles.

Our research team is currently working on developing shared MR environments to allow for more comprehensive collaborative experiences among students. So, as future work, our team aims to refine the MR module and upgrade it from single-user to multi-user operation, allowing for synchronized shared experiences and conducting another research study.

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