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# MIXED REALITY TECHNOLOGY: A VIRTUAL TRAINING TOOL IN FLUID POWER ENGINEERING

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## ABSTRACT

*Fluid power systems can be expensive and difficult to access, making it challenging to provide hands-on training. This work discusses the incorporation of Mixed Reality (MR) technology in Fluid Power applications for providing a virtual training environment that simulates the behavior of fluid power systems, allowing users to receive immediate feedback on the system's performance. Mixed reality is a digitized-based technology that integrates a virtual environment with our real world by utilizing real-world sensor data and computer models. This technology allows running simulations that examine the complexity of highly-coupled systems, producing new digital environments where physical and digital elements can interact in real-time. With all these features, MR technology can be a practical training tool for running virtual simulations that mimic real-life industry settings. It can extend the user with a virtual training environment, thus preparing the next generation of fluid power engineers and specialists. Throughout this work, we present the development and capabilities of a digitized virtual copy of a hydraulic excavator's arm in an MR environment as a proof of concept. The MR arm module is developed and deployed using Microsoft's Mixed Reality Tool Kit (MRTK) for Unity through HoloLens 2 MR headset. The MR development involves generating virtual copies of the mechanical and hydraulic sub-systems, conducting the virtual assembly, and creating a user interface in the MR environment to visualize and interact with the model. The developed MR module enables visualizing the excavator's internal structure, conducting the virtual assembly, and running virtual simulations, all of which assist in training future fluid power operators. It is an effective training tool that helps train junior engineers/technicians, cutting down on cost and time.*

Keywords: Fluid Power, Mixed Reality, Virtual Training, Excavator Arm.

## 1. INTRODUCTION AND BACKGROUND MATERIALS

Several academic and vocational institutions have widely utilized Fluid Power training campaigns to educate and train individuals involved in Fluid Power, like mechanics, engineers, operators, students, etc., to help increase productivity, reduce downtime, and improve safety [1]. Such campaigns aim to provide users with the required fluid power knowledge and engineering skillset to operate, maintain, and repair fluid power systems. They help expose individuals to fluid power fundamentals, like principles of hydraulic and pneumatic systems, fluid power components, fluid power system diagnosis/troubleshooting, etc.

Fluid power training campaigns take several forms, from online training to in-person seminars, workshops, and hands-on training [2]. Among all these forms, hands-on training has drawn the attention of fluid power stakeholders, given the significance of the hands-on experience to train beginners in the fluid power field [3]. One of the most adopted hands-on training is the utilization of hydraulic and pneumatic trainer stands, which are customizable test benches that aim to support hydraulic and pneumatic motion control teaching [4]. Such benches are training equipment comprising a power unit, valves, actuators, and other fluid power components, e.g., hoses, connectors, etc., to provide the user with practical experience in building and operating fluid power systems [5]. Many fluid power companies, like Eaton [6], Parker Hannifin [7], Bosh Rexroth [8], and SAP engineers [9], have designed and implemented these trainers, where universities have adopted them to provide learners with hands-on training. Academic institutions utilize these stands for training fluid power learners (students) and delivering the course topics more enjoyably, engaging the students and helping them acquire the fluid power concepts.

Besides the hydraulic test stands offered by fluid power firms, virtual training stands have also been utilized as fluid power training tools for educating beginner fluid power learners [4], [10], [11]. For instance, in [4], a virtual hydraulic trainer, shown in FIGURE 1, was designed to be incorporated into fluid power labs. The virtual trainer is a computer-aided 3-Dimensional (3D) interface accessible through a computer desktop. It provides fluid power learners with a dynamic interactive learning environment, exposing them to fluid power principles and fundamentals. The virtual trainer allows running multiple experiments with data acquisition at different operating conditions, allowing users to test various cases, observe pressure-flow relationships, and collect and analyze data. Therefore, the virtual trainer helps users practice and refine their skills in a safe controller fluid power environment.

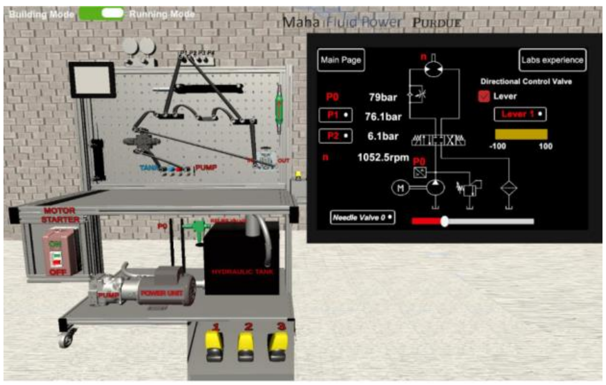


**FIGURE 1:** VIRTUAL TRAINER SIMULATOR LAB DEVELOPED IN [4]

Another computer-aided virtual trainer was designed in [11] to be implemented in fluid power courses. The virtual trainer includes 3D models and simulations for multiple fluid power systems to provide a more interactive and engaging learning experience for fluid power education. FIGURE 2 shows the graphic user interface (UI) for one of the developed fluid power modules utilizing the virtual trainer. The trainer was incorporated in fluid power courses to be evaluated, and the results showed that it was effective in enhancing the learning experience and understanding of power system principles.

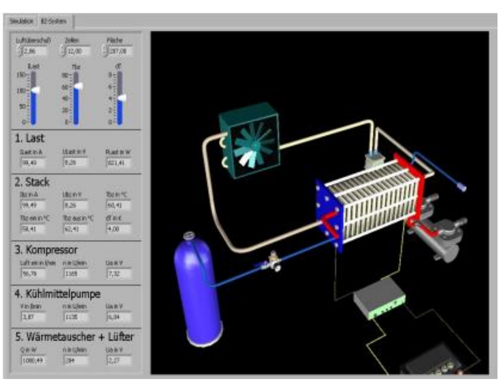


**FIGURE 2:** GUI OF THE VIRTUAL TRAINER DESIGNED IN [11]

In addition to these technologies mentioned above, computer-based simulation modules have been developed and incorporated into the fluid power curriculum to educate and train students, preparing them for their future fluid power careers [12], [13] [14]. For instance, in [12] and [14], fluid power engineering faculty from different universities collaborated with industrial companies to develop web-based teaching modules based on designing CFD simulation software. The goal was to create a beneficial learning environment that increases the students' technical expertise while enhancing their engineering skill set by integrating the developed CFD simulation software into undergraduate fluid mechanics classes and laboratories.

Despite all the adopted fluid power training campaigns to create an effective training environment for fluid power learners, these tools often fall short of exposing learners to real industry scenarios. They still lack the potential to expose the user to industry-like situations due to some arising challenges related to the rapid technological advancement in the design, operation, and control of fluid power systems, the cost of the equipment, regular maintenance, and required space [15]. Such challenges make it difficult to provide the needed hands-on training that aims to recruit the next generation of fluid power engineers.

Therefore, this work discusses integrating Mixed Reality (MR) technology in Fluid Power applications to overcome some of these challenges. This work presents the development and capabilities of an excavator's arm's MR module as a proof of concept. It shows the development of the digitized virtual copy of the hydraulic arm in an MR environment. It can be utilized as a virtual training tool for conducting several activities mimicking the hands-on experience in future training/learning campaigns.

The rest of this paper is structured as follows. Section 2 introduces MR technology, its versatile features, and how it is used in various fields to improve the user's experience. This section also discusses the advantages of using MR as a training tool in fluid power applications; an excavator's arm is used as a proof of concept. Section 3 presents the excavator's arm mechanical and hydraulic designs, highlighting the system's features. Section 4 exhibits the development and implementation of the excavator's arm MR training module and its capabilities in providing a good training experience. Finally, Section 5 provides a conclusion on the work.

## 2. MIXED REALITY TECHNOLOGY: A VERSATILE TOOL

Mixed reality technology is an immersive digitized-based technology that combines virtual reality (VR) and augmented reality (AR) to extend the user with a new reality where virtual and physical objects can coexist and interact in real-time [16]. Unlike VR, which immerses the user in a virtual environment, MR maintains a connection with the real world, allowing users to interact with their surroundings, thus providing a new visceral experience [17]. This technology uses advanced visualization media to introduce users to a new mode of visualization, which facilitates the overlay of rendered visuals on reality [18]. It employs mounted displays allowing the user to see virtual objects overlaid in the real world [19]. It is recognized as a potential future transformation of the human-machine interface in the real-virtual environment [20].

With all these features and high potential to enhance the user's experience, MR technology has been utilized as an educational and entertainment tool in various domains, such as engineering, healthcare, biomedical, and medical fields [21]–[24]. For instance, in [22], MR technology has been adopted to expose Biomedical Science students to regenerative concepts and tissue engineering processes and thus evaluate the user acceptance of MR technology in biomedical education. Throughout this work, an MR platform called the Mixed Reality Regenerative Concept (MRRC) was developed for conducting a research study that aims to explore the factors that influence user acceptance and determine the level of user satisfaction and intention to use MR technology. 116 participants from different backgrounds and ages were recruited to evaluate their perceptions of MR technology. The data were collected using a questionnaire based on the Technology Acceptance Model (TAM) and analyzed using descriptive statistics and regression analysis. The results highlighted the importance of designing MR applications that are user-friendly, useful, and enjoyable to encourage user acceptance and adoption.

Given the promising results of utilizing MR as an educational/entertaining tool, this work proposes using MR technology as a training tool to address some issues associated with fluid power engineering training, like the cost of equipment, maintenance, available lab space, components manufacturing, etc. Incorporating MR technology into fluid power training has many advantages, enhancing the overall training outcomes (see Figure 3).


**Figure 3:** MIXED REALITY TECHNOLOGY: A TRAINING TOOL

As illustrated in Figure 3, such integration provides a more comprehensive context by permitting trainees to experience more realistic situations in an industry-like setting [21]. This approach also enables the delivery of more authentic courses by exposing trainees to real-life career settings through immersive artificial experiences. It can help fluid-power learners acquire concepts by applying theoretical knowledge to real-life situations. Additionally, MR technology can promote spatial-visual abilities in individuals by addressing spatial visualization challenges using virtual-real object interaction principles [25]. By allowing users to interact with 3D digital objects in an extended environment, MR technology can aid in developing spatial skills. For instance, users can merge their substantial environment with the pre-designed virtual world through a smooth human-computer interface, providing a more engaging and practical learning experience.

As a proof of concept for incorporating MR into fluid power engineering training, an MR training module on an excavator's arm is developed to be integrated into future training campaigns. The following section summarizes the mechanical and hydraulic design of the intended excavator's arm.

## 3. EXCAVATOR ARM MODEL

The excavator's arm utilized for developing the MR training module is a miniature and portable fluid power demonstrator comprising hydraulic and mechanical sub-systems. It is versatile and applicable to diverse training settings involving internships, recruitment events, senior projects, etc. Besides training, this excavator arm could also be used as a pedagogical tool to teach fluid power students at university levels by exposing them to mechanical and fluid power concepts, thus assisting in acquiring the sought-after fundamentals. For instance, as a learning tool, it could be involved in a wide array of courses, ranging from fundamental engineering courses like statics and dynamics to more advanced courses such as fluid power and data acquisition.

The following sub-sections introduce each of the hydraulic and mechanical sub-systems of the excavator's arm and present the developed prototype.

### 3.1. Mechanical Sub-system

The mechanical sub-system is the excavator arm's structure, consisting of the main rotating base, boom arm, dipper arm, and bucket, as shown in Figure 4. The system also involves the tool chest that stores the hydraulic sub-system components and allows the excavator's arm to be mounted.

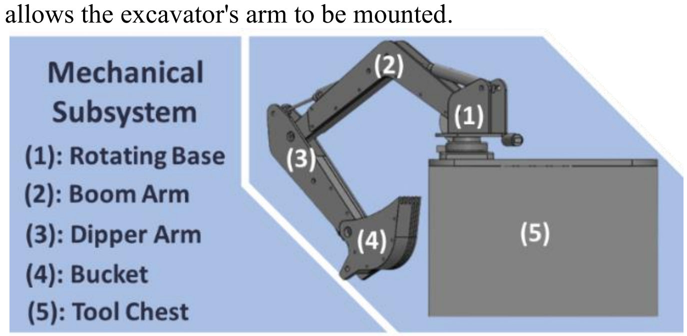


**Figure 4:** EXCAVATOR MECHANICAL COMPONENTS

The mechanical model of the arm was designed using SolidWorks in two main phases: Phase 1 involved Geometry Calculations, and Phase 2 focused on determining Force Requirements.

**Phase one** was pivoted on determining the excavator's geometry by incorporating the standard geometric design commonly found in the excavating equipment industry for locating the mounting holes. After determining the mounting holes, the arm's geometry was tested using SolidWorks to ensure appropriate arm rotation, i.e., preventing the arm from rotating back into the tool chest or hitting the ground. Then, statics analysis was conducted in **Phase Two** to determine the force requirements for lifting the excavator's arm. Thus, the arm was analyzed in SolidWorks at its critical configuration, i.e., the position allowing it to rotate down to a level suitable for excavation at a shallow depth of a few inches above the ground. This was done by extending the arm to its farthest extending position, which is the location of the boom arm actuator that exerts the minimum force in the vertical direction. Subsequently, the total weight of the arm (including the hydraulic actuators) was determined, enabling the calculation of the force necessary to counterbalance the arm's weight. The computed value of the force was *F=36.43 lbs.*

### 3.2. Hydraulic Sub-system

The hydraulic sub-system is responsible for controlling the excavator's arm, i.e., rotating the base and positioning the boom, dipper, and bucket. It comprises the fluid power supply components, i.e., the hydraulic pump, four linear actuators (one for the dipper, one for the boom, one for the bucket, and one for base rotation), solenoid valves, flow control valves, and other fluid power components, like fittings, hoses, and tubing. The main hydraulic components, like the cylinders and the pump, were sized and selected by conducting hydraulic calculations based on geometry computations and force requirements. Given the hydraulic calculations, the following hydraulic components were selected:

**Table 1:** HYDRAULIC COMPONENTS' SPECIFICATIONS

| Component | Specification |
|---|---|
| Pump | 100 psi and 1.6 GPM |
| Boom's Hydraulic Cylinder | 7/8'' Bore and 3'' Stroke |
| Dipper's Hydraulic Cylinder | 7/8'' Bore and 3'' Stroke |
| Bucket's Hydraulic Cylinder | 7/8'' Bore and 3'' Stroke |
| Base Rotation Hydraulic Cylinder | 7/8'' Bore and 1.5'' Stroke |

Figure 5 shows the hydraulic circuit of the excavator's arm, which consists of a hydraulic pump (1) and the four sub-circuits, one for the boom positioning, one for the dipper positioning, one for the bucket positioning, and one for the base rotation. Each of the four sub-circuits comprises a 4/3 DCV (3), metering out flow control system (2), and hydraulic cylinder (4), all of which are capable of handling *150 psi*. The 4/3 DCV is closed-center with spring return having two directly actuated solenoid coils, which allows for a seamless operation while lifting and controlling the excavator's arm. Besides the 4/3 DCV, the metering-out flow control system (3) consists of two flow control valves, one at the inlet (left) and the other at the outlet (right). The control valve at the inlet controls the retraction of the actuator, and the control valve at the outlet controls the actuator's extension.

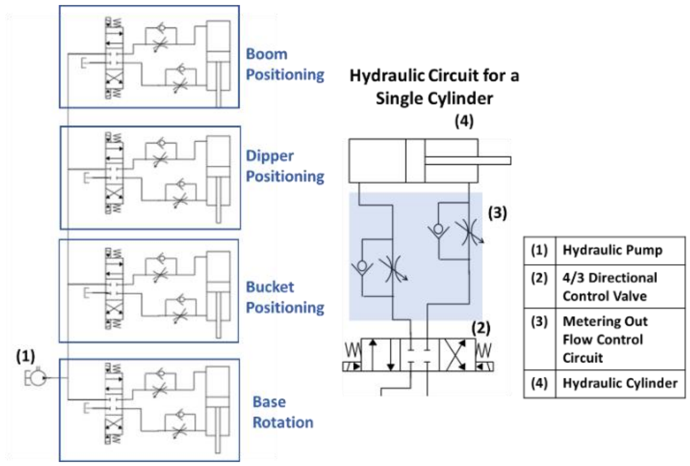


**Figure 5:** HYDRAULIC CIRCUIT OF THE EXCAVATOR'S ARM

### 3.3. Developed Prototype

After designing the mechanical and hydraulic sub-system, a portable prototype of the excavator's arm was built to be used as a fluid power training and educational tool, as shown in Figure 6. One of the main goals was to have a light-weighted portable prototype that allows teaching the sought-after fluid power concepts in a safe environment. Thus, for safety procedures and to save money and achieve the required goal, a pneumatic circuit was replaced by a hydraulic circuit. As shown in the Figure, the adopted pneumatic circuit comprised the main pneumatic components (air compressor, pneumatic cylinders, and pneumatic valves) besides other pneumatic components. Furthermore, the arm was built using Lexan sheets, allowing the system to be transparent, thus permitting trainees to observe the mechanical components from multiple angles during operation. Given its features, this prototype served as a good training demonstrator for fluid power campaigns and engineering workshops, providing fluid power learners with the required hands-on experience [26], [27].

**Figure 6***:* THE EXCAVATOR'S ARM PROTOTYPE [26]

However, utilizing the arm in large-scale training campaigns requires building and designing multiple hands-on kits with the proposed hydraulic circuit (mechanical/hydraulic parts), which can be time- and money-consuming, hard to manufacture, and thus unaffordable. For this reason and given the applicability of MR technology in improving the user experience, an MR module for the excavator's arm is developed as a proof of concept to allow for providing a virtual training environment that simulates the behavior of the fluid power system, allowing users to receive immediate feedback on the system's performance. The MR module enables integration of the virtual copies of the fluid power system in our real physical world to enable running simulations examining such systems' complexity.

## 4. MR DEVELOPMENT AND IMPLEMENTATION

An interactive MR module for the excavator's arm was developed for future fluid power training and education campaigns. The following two subsections discuss the MR project development, setup, and capabilities.

### 4.1. MR Project Setup/Development

Figure 7 shows the MR project setup process, highlighting the different software employed for setting up the MR environment and developing the excavator's training module. As shown in the Figure, throughout the MR module development, *Unity* 2021.3.16 Software, a cross-platform game engine developed by Unity Technologies [28], is utilized to design and implement a 3D digital representation of the excavator's arm in a spatial interactive MR environment. After developing the CAD model in SolidWorks, it needs to be optimized and converted from an ***STL*** file into ***FBX*** file, which Unity supports. For this reason, *Blender* software, an open-source 3D computer graphics [29], is also utilized as a window file conversion, allowing converting the file conversion format to be readily imported as object assets into *Unity*. *Blender* is then used to create the excavator's animations and motion simulations. Besides importing the CAD files, it is required to set up the Mixed Reality playspace by downloading the ***(Mixed Reality Feature Tool Kit)*** Application [30]. This application serves as a platform that allows developers to add and update MRTK packages in *Unity* projects. Thus, this application allowed adding the four MRTK packages (MRTK Foundations, MRTK Extensions, MRTK Test Utilities, and MRTK Tools) to the Unity project.

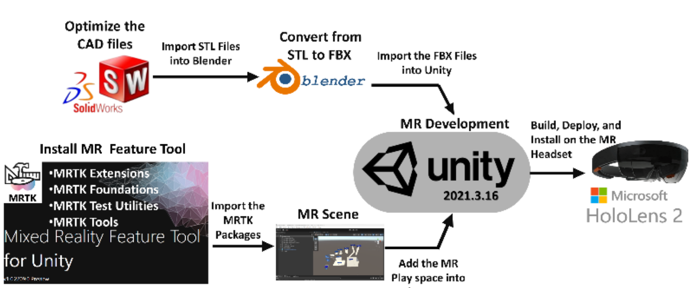


**Figure 7:** DIAGRAM ILLUSTRATING THE MR SETUP

The CAD files and the MRTK packages were imported into Unity to develop the MR module, which was then built and deployed on Microsoft Hololens 2, a holographic device designed and manufactured by Microsoft. Thus, the imported assets (Excavator's arm 3D components) were organized and sorted into two groups (hydraulic and mechanical sets) in the required scene as unity game objects. Then, unity scripts were created and compiled using `(UnityEngine)`, `(UnityEngine.Events)`, `(Microsoft.MixedReality.Toolkit.UI)`, and `(HoloToolKit.Unity.Buttons)` to allow for various types of interactions, like grabbable interchange and near and far object manipulation. The scripts also allowed for spatial awareness, eye/hand tracking, and user UI controls that support HoloLens 2 articulated hand input. This adopted procedure enabled the creation of a UI MR setting to visualize and interact with the excavator's arm components, like touching, manipulating, conducting assemblies, etc. The project was then built, deployed, and installed on the HoloLens 2 headset.

### 4.2. MR Module Capabilities (Activities)

The MR module is convenient for fluid power training campaigns, given its versatile activities that fluid power learners could conduct. The developed MR module comprises three main activities (Activity 1: Components' Sorting, Activity 2: Excavator's Arm Assembly, and Activity 3: Motion Simulation), as illustrated in Figure 8.

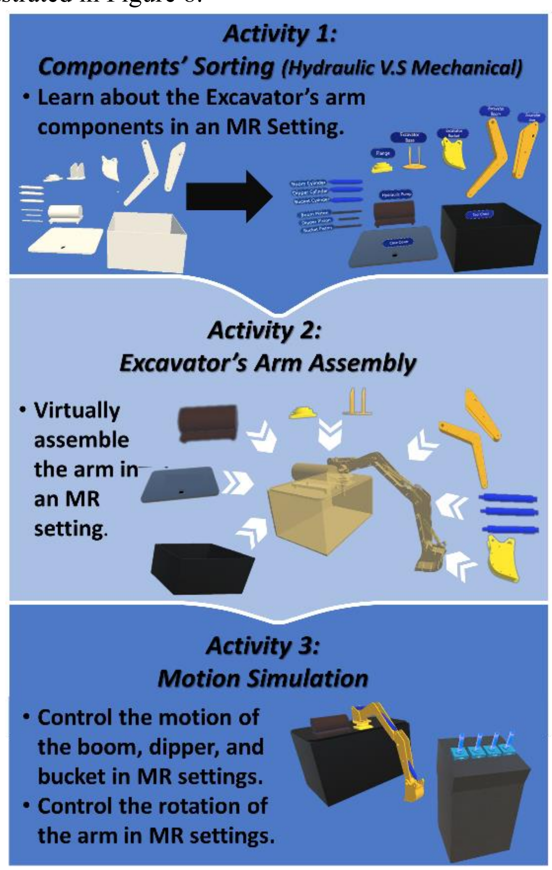


**Figure 8:** DIAGRAM ILLUSTRATING THE MR MODULE CAPABILITIES

### 4.2.1. Activity 1: Components' Sorting

**Activity 1** is designed to expose fluid power learners to the excavator's arm sub-systems (hydraulic and mechanical sub-systems) and their associated main components in MR settings. This activity utilizes hand tracking to allow fluid power learners to interact with the arm's components by virtually touching and grabbing each part using their hands, thus identifying and sorting the arm's pieces into hydraulic and mechanical sets. Furthermore, it gives learners an in-depth understanding of the system's technical aspects by displaying the components' technical information and specifications right after being touched, as shown in Figure 9.

As the Figure shows, visual indications, such as color changes, are employed throughout this activity to facilitate user interaction with the digital representations of the excavator's arm basic components, thus enhancing the user's experience. Specifically, after touching a component, its color changes from white to its original color, providing users with immediate feedback on their interaction with the component.


**Figure 9:** CONDUCTING ACTIVITY 1 (DISPLAYING TECHNICAL INFORMATION)

### 4.2.2. Activity 2: Excavator's Arm Assembly

After completing Activity 1, the users will start **Activity 2,** which allows them to assemble the excavator's arm virtually in an MR setting using their hands, providing another form of interaction. Throughout this activity, users (fluid power learners) will assemble the excavator's arm in a defined sequence, thus learning about the assembly-disassembly procedure (see Figure 10). As shown in the Figure, the user needs to grab the correct component, manipulate its orientation/configuration, and assemble it in its proper spot on the transparent excavator's arm structure.

Similar to Activity 1, visual aids are utilized to guide the trainees through the assembly process. For instance, all the components are initially displayed in white while highlighting the component that should be assembled. Furthermore, when the user makes three incorrect attempts, the corresponding spot for the arm's component will be highlighted in a different color on the arm's structure to assist in correct placement.

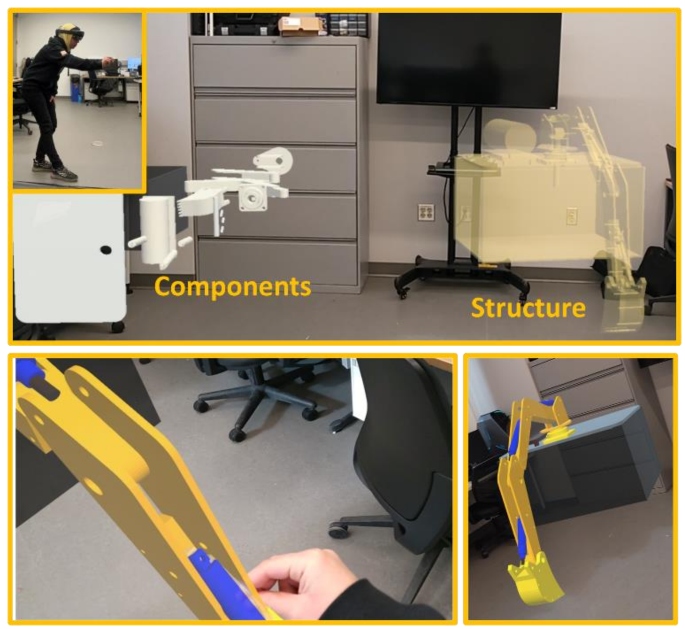


**Figure 10:** CONDUCTING ACTIVITY 2 (EXCAVATOR'S ARM ASSEMBLY)

### 4.2.3. Activity 3: Motion Simulation

Finally, **Activity 3** is a vital part of the MR training module as it enables the trainees to study and inspect the excavator's arm mechanism by using virtual UI controls to simulate the motion of the arm. Figure 11 shows the virtual UI control stand comprising four Joysticks. The first three Joysticks allow controlling the position of the boom, dipper, and bucket, while the fourth Joystick is used to control the rotation of the arm. By utilizing this virtual UI control stand, trainees can explore the complex mechanisms of the excavator's arm in a controlled and safe environment, exposing them to the excavator's arm functions. This virtual motion simulation allows trainees to run realistic simulations at different operating conditions, thus assisting in predicting the arm's performance. Besides testing the arm's mechanism, this activity can enable users to understand better the various safety protocols that must be observed when operating an excavator's arm. Activity 3 offers a practical and effective approach to excavator arm training, ensuring that trainees are well-prepared to handle the equipment when they enter the workforce.

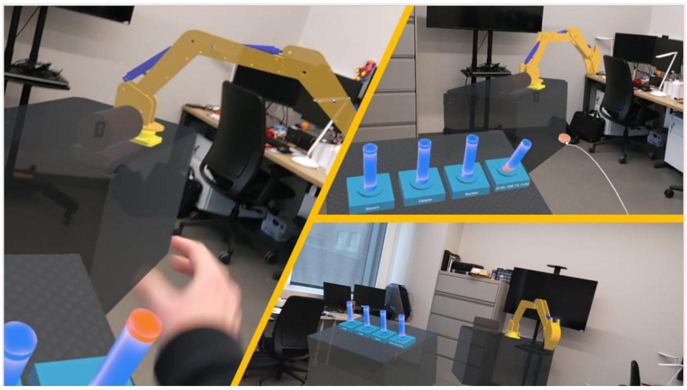

**Figure 11:** CONDUCTING ACTIVITY 3 (MOTION SIMULATION)

## 5. CONCLUSION

Training campaigns show significant importance in fluid power engineering applications, given their applicability in providing users with the required Fluid Power knowledge and engineering skillset to operate, maintain, and repair fluid power systems. However, such campaigns require utilizing physical fluid power equipment, which might be costly, challenging to access, and require regular maintenance. Therefore, this work presents the incorporation of MR technology into fluid power training, given the potential of this groundbreaking technology to simulate the behavior of fluid power systems in an industry-like setting, thus improving the user's experience. For this reason, an MR module of a miniature excavator's arm is developed and implemented as a proof of concept. The module comprises three primary activities, allowing trainees to visualize the excavator's internal structure, conduct the virtual assembly, and run virtual simulations. This module can potentially train fluid power operators effectively, serving as a cost-effective and time-saving training tool for junior engineers/technicians. The MR module will be optimized to be incorporated into Fluid power training courses as part of future work. A further research study will be conducted to assess the module's technical and training aspects.

## ACKNOWLEDGMENT

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