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Mixed Reality for fluid power instruction

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1) Abstract

Fluid power education is most effective when conducted with hands-on applications and real-life projects. To optimize the students' understanding of fluid power systems, they need to interact with individual components and systems made by these components, ideally during their operation. However, this effective and widely implemented approach is limited in execution because of safety concerns, budgets, the number of participants, visibility, and available space. In addition, physical testing environments must be properly instrumented to showcase system changes and operations, which can be costly and time-intensive. This work showcases a solution to these challenges by introducing a fully immersive and interactive Mixed Reality (MR)/Virtual Reality (VR) laboratory for gear pumps. The laboratory exercises allow students to interact with parts and/or systems in a safe and immersive manner and help them gain knowledge using guided tutorials. This is achieved using Microsoft HoloLens, mixed reality smart glasses, to present students with interactive CAD models of assembled fluid power components and a tablet computer used for virtual interaction. This paper presents the procedures and materials used to create both a virtual gear pump and a relief valve, including their virtual assemblies, computational fluid dynamics, and animation of the parts interacting within them. The MR and VR devices show instructions and advice so that students may learn how the components and the fluid operate within a component and offer interactions with their moving parts to identify their individual parts. This allows students to identify the parts of a pump and assemble them. Three programs are used in conjunction with the Microsoft HoloLens and a tablet to create interactive experiences: (1) Autodesk Inventor Pro is used as the CAD modeling software to build virtual parts, (2) Unity functions as the environment building an engine to house the project and (3) Ansys CFX for the fluid simulation to understand how the fluid behaves in the parts. In this paper, the authors demonstrate how these instructions are created and modified in real-time to better suit the needs for instruction and training in the fluid power classroom.

2) Introduction

Fluid power is a ubiquitous technology used in various fields (manufacturing, automotive, aerospace, mining, etc.). Fluid power includes a range of devices and applications and includes hydraulic (liquid-based) and pneumatic (gas-based) systems. Fluid power components include pumps, motors, valves, pistons, and numerous other devices combined into hydraulic circuits to complete a task. Fluid power systems produce high power compared to electrical systems, which is why they are used in large-scale applications. This is highly beneficial in the real-world, but makes it challenging to teach safely and effectively in a classroom setting. Students learning fluid power need hands-on experience adjusting components, pressures, and flows to see and understand the effects of hydrostatic pressure. However, this can cause safety hazards. For this reason, it is necessary to leverage practical hands-on experiences using MR/VR.

Conventional methods enabled the adoption of knowledge and skills (problem-solving, experimentation, and data analysis) through direct contact with physical environments in controlled and limited settings. For example, students will use a gear pump in a hydraulic circuit and see a drawing of the pump's inner workings. However, they cannot take the pump apart, and they can only adjust pump parameters within a specified range to prevent damage to the device. In this active learning approach, learners are more likely to meet learning objectives in a controlled and the designed environment through expanded interactions with the hydraulic system using MR/VR.

The tools used for instruction in hydraulic and pneumatic systems have primarily been based on components or computer simulation tools that imitate a real hydraulic or pneumatic system. Both teaching methods rely heavily on the availability of the equipment (components) or computer licenses to build systems, thus limiting the concepts taught to the students. Many training stations have been developed for instruction in fluid power courses. A great variety of exercises have been developed to teach general concepts regarding fluid pressure build-up in a system, fluid mechanics principles to model flow through an orifice, or concepts in control theory. Examples of traditional trainers are shown in figure 1. A few companies produce fluid power training equipment for instruction in academic or industrial environments. These companies include Parker Hannifin, Eaton, Bosch-Rexroth, FTPI, Festo, Hytech, FTPI, and Amatrol [1].

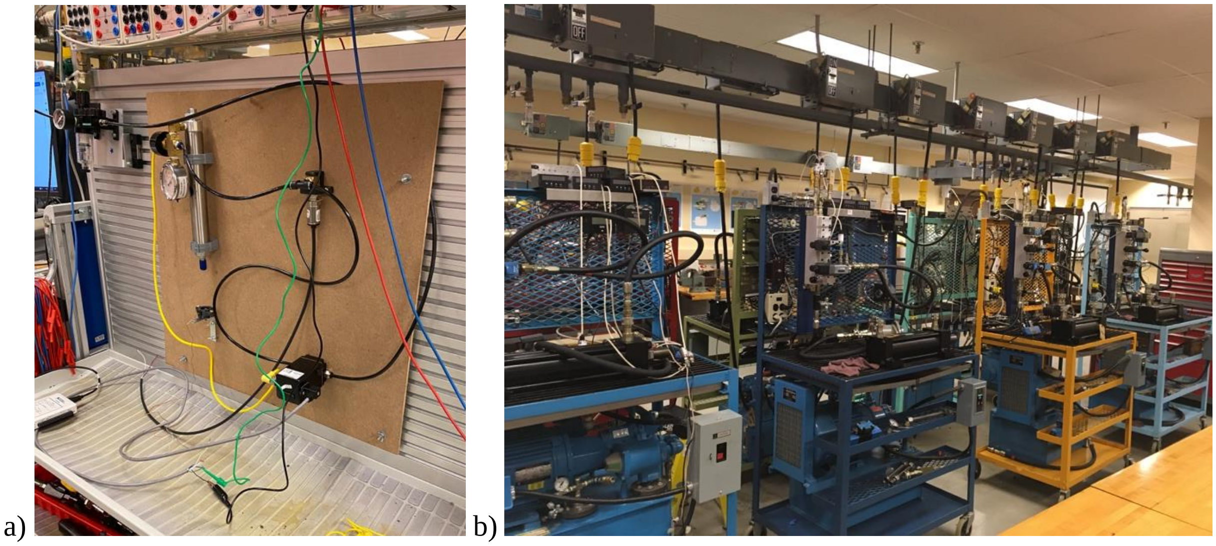


Figure 1. Traditional fluid power trainer with mountable or fixed fluid power components

Most of these trainers can be customized. However, once the trainer is configured, the modules taught are limited to the specific components available on the trainer. Moreover, these trainers require that the students interact with the systems in person, which creates logistical problems regarding class sizes, space, and the high cost of trainers. The restrictions caused by COVID-19 also imposed limitations to the use of fluid power training stations for instructional use since much of the in-person learning was pushed online. The trainers are also designed for fluid power circuits with controlled inlets, outlets, and reservoirs. This is important for cost, safety, and cleanliness. However, this makes it a challenge to teach students about the parts that make up a system individually. The traditional tools for teaching components are expensive cutaways, and more recently, animated CAD representations of these various parts. Yet, the most valuable and effective method for teaching about the elements is teardown and reassembly [2].

Experiential learning has demonstrated success in a variety of classroom settings [3], [4]. And now, the virtual learning space has started to play a role in classrooms and training programs. This approach is conducive to reaching the same and expanded learning objectives with increased safety, reduced cost, higher adaptability, and deployed to a larger number of individuals without sacrificing hands-on components. Moreover, learners work in an immersive and safe environment and may still work cooperatively even though they may not be physically present in the same place. They can continuously acquire new knowledge while avoiding external distractions associated with physical experimentation.

Various examples of novel fluid power training stations have been described in literature [5] [6]. But only until recently have instructors dealt with the use of remote or virtual tools for interacting with the existing equipment, yet none of them have made use of MR or VR tools for interaction with the trainer or a virtual object in real-time [7]. Zhao et al. [8] proposed an approach to a virtual tour of a laboratory facility and the operation of a virtual centrifugal pump that could be operated using VR goggles. Although there are many new tools available for teaching fluid power at the system level, there is a need to develop Extended Reality (XR) tools for instruction focused on the components, where XR combines the real and virtual environments with human-machine interactions. This research project aims to create virtual tools for teaching the components necessary for building fluid power systems. Specifically, this paper will showcase a laboratory for teaching students how gear pumps work, including a virtual laboratory with tear down and assembly of its inner components.

3) Literature Review

A broad range of technologies exists for virtual learning, where applications are displayed in 2D [9] and 3D formats [10]. Virtual reality is a 3D immersive environment supported by head-mounted displays (HDM) [11]. These devices allow a full or partial immersion. A good example of partial immersion is mixed reality (MR). MR is a hybrid environment where virtual or computer images are overlayed over a real view [12]. An example of this is shown in figure 2.

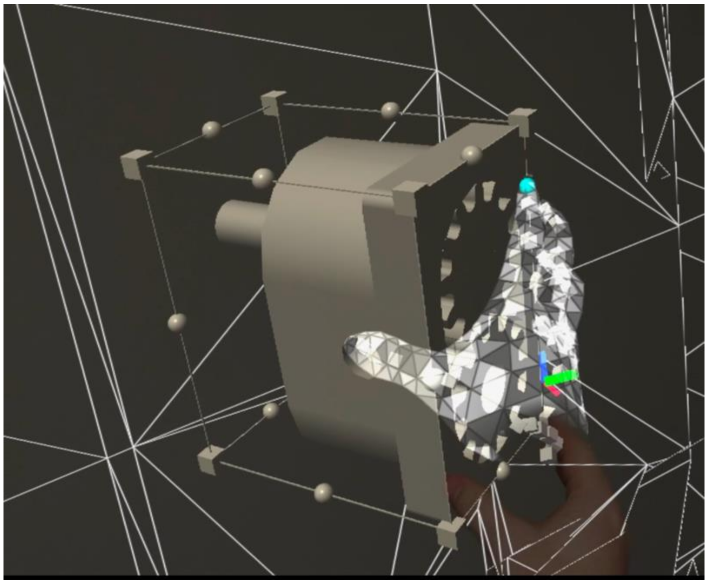


Figure 2. Mixed reality representation of a Gear pump assembly

In MR, the physical and virtual worlds are merged and create an enriching experience combining both worlds. Mixed reality has enabled the possibility of moving forward quickly in phenomenon understanding and reinforcing former learning techniques. This approach has started to be implemented by enterprises for training purposes. Companies, such as Festo [13], have a training program where MR serves as guidance to assemble pneumatic circuits and more complex systems. As Festo itself claims, this computer-aided system prevents users from life-threatening or hazardous situations (environment and machinery). To emulate an experience close to real-life situations, they developed CIRO VR, a software whose main features include real-time results, in interactive and 3D simulation.

Other companies, such as Bosch, are also advancing in this area. They use MR to implement maintenance programs remotely, such as those reported by Neges et al. [14]. As a result, workers can carry on hands-on tasks without using physical manuals or guides. Furthermore, Bosch points out that mixed reality is the future of an immersive interactive environment that will also support marketing, repair, and training within a company [15].

In the same path, the work presented in [16] combines a remotely controlled (RC) excavator (Kobelco) and virtual reality (VR) to evaluate the skill of operating a hydraulic excavator. The author resolves the dynamic movement of the excavator by using a mathematical model. These calculations are used as input data for the simulation in the virtual application and are then calculated for multiple cases (boom, arm, and bucket angles). Consequently, this author and others [17] found that it is possible to boost operator skills through virtual models. However, this methodology does not replace all possible scenarios inherent to the actual operation of a heavy-duty construction machine. It is worth noting that VR methods do not allow operators to interact with the surroundings unless they are also simulated using physics-based models.

In addition to MR applications for enterprises, universities are also taking the lead in this field [18]. Classrooms are becoming a part-virtual laboratory environment where traditional lectures are left behind [19]. [17] shows how students benefit from this approach by way of illustration. In this study, researchers have re-created both a virtual civil engineering hydraulic laboratory and virtual flowmeters from scratch. The research was designed to reduce the risk of interacting directly with an environmental civil engineering setting and develop an educational tool that students can help improve by providing their feedback. In its final version, students accomplished the characterization of an open-channel flow.

Other technologies combined with MR have given rise to new developments. In fluid mechanics applications, Computational Fluid Dynamics (CFD) solve the governing equations of fluids numerically. However, the results of simulations conducted by CFD are displayed in 2D devices (screens), which makes it cumbersome to visualize and understand 3D representations. That said, mixed reality serves as an immersive tool not only to visualize the flow itself but to allow the user to be virtually immersed in it. This can be illustrated quickly in the studies by [20], [21], [22]. The authors simulated the thermal change process in a university room and animated it in a head-mounted device (HMD). This methodology facilitates the rapid iteration of different conditions (temperature changes and materials properties). In a fluid mechanics or fluid power classroom, the visualization process for designing a virtual lab involves several steps from the CAD modeling of the component to the fluid simulation results in a virtual environment. Authors [23], [24] propose a workflow for the visualization process. However, the main limitation is that it is still a challenge to obtain CFD results in real-time to be visualized in virtual environments.

What makes all these studies similar is that they take advantage of head-mounted devices to visualize virtual laboratory spaces. Thus, users have their hands free to interact with the surroundings and learn from the designed environment, where knowledge is transmitted effectively regardless of the field of study. Indeed, this approach does not resemble experimentation in the real world; users do not perceive the same physical sensation when touching holograms as they do from touching real objects. However, XR (Virtual or Mixed Reality) is a promising tool that makes students acquire knowledge and save money in the long run.

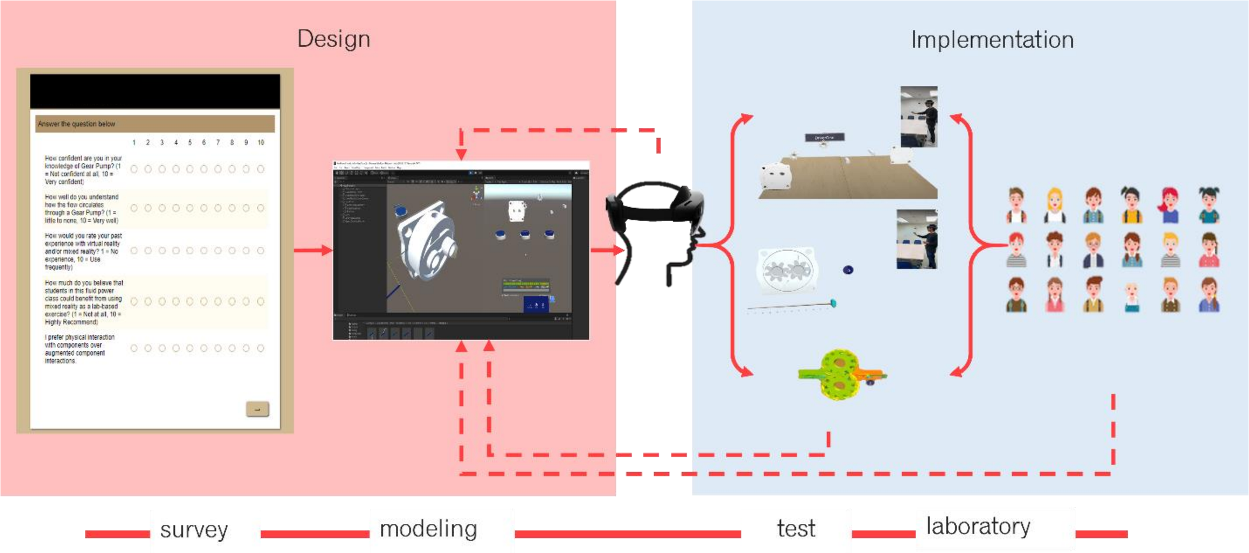
4) Reported uses of Mixed Reality in the classroom

Virtual reality and mixed reality are used across educational institutions as needs grow for better and more immersive learning and more robust distance education options. The development of VR instruction is viewed as the most effective way to combat these changes in education that the COVID-19 pandemic has primarily brought about. One example is an automotive course created using the Oculus Rift and Leap Motion devices. Two environments were created for the course using SolidWorks® and the Unity3D Game Engine® Software. The researchers compared the results of students with differing backgrounds in automotive systems by asking them to rate the two systems after use. The Oculus Rift scored slightly higher in all categories rated, with “Motion sickness” being notably better in the Oculus than in the Leap Motion Controller [25].

Previous studies have shown MR and VR as beneficial for students within a classroom setting regardless of their XR-related backgrounds. One of the fundamental practices taught within engineering is the skill of geometric visualization; being able to mentally view what an object looks like from all sides. It was found that students with no visualization experience benefitted more from MR being implemented than students who had previously been exposed to it or were avid gamers. Students with no CAD experience but who played video games at least 3 hours a week were much more advanced in their ability to visualize a two-dimensional object in a three-dimensional context than students who had prior CAD knowledge [26]. Likewise, chemical engineering education's adoption of VR has shown much in the way of technical opportunities and challenges, educational implications, and economic and social challenges. Currently, the use of VR in chemical engineering education is mainly for visualization purposes, but with mathematical modeling, dynamic processing can be used to better instruct students. One of the challenges faced was the willingness to accept these technologically advanced educational practices by both students and educators alike. While VR shows many benefits associated with distanced learning, the lack of ability to visualize mathematical formulation is a concern [27].

Huang and Roscoe [28] reported that head-mounted display-based VR had not been tested in the engineering education field as it has in other areas of education. According to these researchers, out of the 47 papers they selected for review, the most prevalent VR applications for engineering education were concerned with assembly and training. This review found that Survey Rating was by far the most common form of evaluation, with 21 papers using this method, others included Interviews (9), Exam Scores (8), Task Completion Times (7), Real-Time Observations (5), Open Questions in Surveys (5), Video Recordings (3), and Case Studies (2). Survey ratings and other methods have not been discussed in detail. Comparing traditional and VR educational delivery methods, VR laboratories were found to be helpful for students that could not attend physical lab experiments [21]. These authors noted that learning theories is not typically considered when developing VR educational applications. Physiological and mental effects of using VR were also a significant problem for users. A primary concern was being distracted from the task at hand in education. It is important to note that this claim was about VR head-mounted devices that immerse students entirely in a virtual environment. According to Soliman et al. [29] VR is a viable engineering education tool, but the designers must be conscious of the application's goal and the user's comfort. It has been shown that MR and VR directly and positively impact students' ability to learn. VR instruction does have a significant impact on cost reduction within educational settings by removing the need for large and expensive equipment and the large infrastructure needed for such traditional laboratory spaces. One drawback to using VR instruction is that labs must be created very carefully not to leave out any small but vital piece of information. They note that continuous updating of labs is necessary, which can take time as including feedback on every new addition is imperative to ensure quality in educational practices.

In summary, VR/MR implementations methods in engineering education are growing rapidly, but many of the testing methods remain the same. There is a need for new and more informative assessment methods. Most research on VR in education has focused on user feedback, and the vast majority has focused on the positive aspects that VR education brings. It can be very beneficial to include the drawbacks of VR instruction within data collection and laboratory reviews. A cost-benefit analysis regarding the creation time and the time spent training people to use VR applications may help understand its deeper effects on education. Mathematical formulations cannot yet be given or displayed using these methods; therefore, a hybrid learning experience of traditional classroom instruction and VR laboratories must be used [27]



[redacted]

Answer the question below

	1	2	3	4	5	6	7	8	9	10
How confident are you in your knowledge of Gear Pump? (1 = Not confident at all, 10 = Very confident)	○	○	○	○	○	○	○	○	○	○
How well do you understand how the flow circulates through a Gear Pump? (1 = little to none, 10 = Very well)	○	○	○	○	○	○	○	○	○	○
How would you rate your past experience with virtual reality and/or mixed reality? 1 = No experience, 10 = Use frequently)	○	○	○	○	○	○	○	○	○	○
How much do you believe that students in this fluid power class could benefit from using mixed reality as a lab-based exercise? (1 = Not at all, 10 = Highly Recommend)	○	○	○	○	○	○	○	○	○	○
I prefer physical interaction with components over augmented component interactions.	○	○	○	○	○	○	○	○	○	○

Figure 3. Virtual laboratory stages

Considering the existing reported studies and the need to implement virtual reality and mixed reality in the fluid power classroom, the objectives of this paper are to create an immersive model for fluid power classes employing HoloLens 2 using a gear pump as an introductory pilot study. This virtual model will enable complete comprehension of how a gear pump works. This study considers the assembly process, the interaction between the rotatory and stationary parts, and accounts for how the flow goes through the gear pump. Figure 3 demonstrates the methods used in this paper- Design and Implementation. The design process starts with a survey. This resource measures previous student knowledge of the pump and how feasible it is to respond positive comprehendely to virtual labs. Based on the fluid power course's needs and the partial survey results, it is possible to model the gear pump lab, the second part of the design stage. In the design-implementation process, the user plays an important role. This individual is in charge of testing the lab and reporting feedback to iterate on the gear pump lab design for the final step, which is classroom implementation. A detailed view of these steps is provided in the subsequence section of this study.

5) Case Study: Hydraulic External Gear Pump

It is impossible to talk about fluid power without a fluid or even a pump to transport the fluid. It is valuable for training or educational purposes to elucidate what is occurring inside the pump when interacting directly with the fluid. As a result, there are some mechanisms to comprehend how hydraulic components work (e.g., Gear Pump). Traditional cutaway models provide users with a representation of these components. However, they lack interactivity and provide limited to no information on flow patterns in real-time. The current study serves as a bridge between the current technology and the future of new interactive MR labs. However, developing these kinds of labs is not straightforward. There are key steps to be followed to build a mixed reality environment. The diagram in figure 4 represents each step taken in this process.

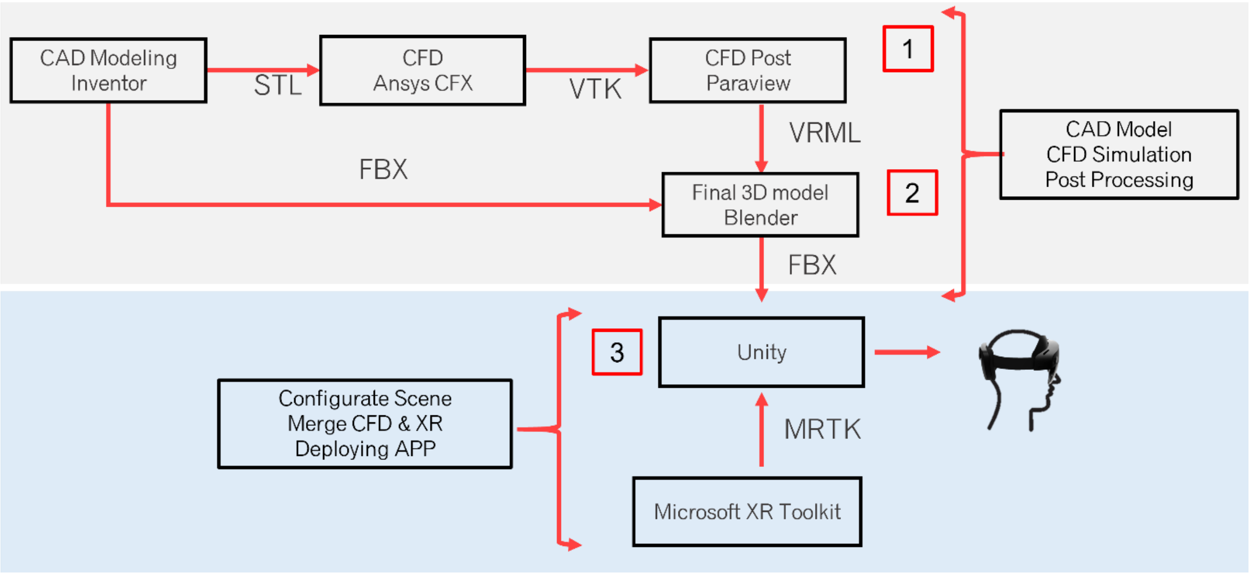


Figure 4. Workflow to develop XR environment for HoloLens 2. Grey regions represent 3D modeling. The blue zone shows the laboratory design process and its implementation.

The workflow to create an app is broken down into two main parts, as presented in figure 4. The first part, the grey region (top), consists of preparing the 3D models, including Computational Fluid Dynamic (CFD) simulation results. The second part, the blue zone (bottom of figure 4), addresses the final app deployment's virtual environment design. As for the first part, the 3D model designs were implemented using Inventor Autodesk to create the gear pump CAD representation. Since CAD formats are not supported in Unity 3D, Blender, a free open-source computer graphic software, transformed all files into a readable format for Unity. In parallel to this process, simulations were run in Ansys Fluent (CFD Package) to capture the flow path inside the hydraulic pump. The operation conditions of a gear pump were set as follows; the working fluid is an oil with a density of 860 kg/m^3 at 20° C. The inlet pressure and the gears' angular velocity were set to 1 atm and 2500 rpm. The simulation converged, and the results were exported into Paraview for obtaining the velocity and pressure profiles at different planes.

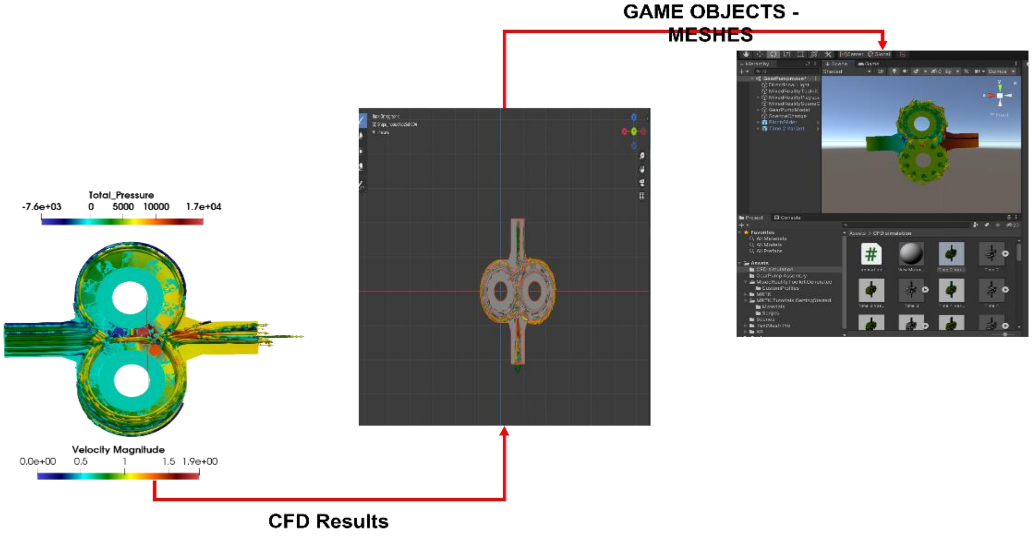


Figure 5. deploying CFD results to Mixed Reality environment

Once the 3D model for the CFD result was exported into Unity, the next step was to start with the design of the virtual lab, as shown in Figure 5. This virtual lab focused on addressing one of the learning objectives for the advanced fluid power class (*How flow and velocity, pressure, and force are related in a hydraulic circuit when external loads, friction, and leakage are considered*). To provide a complete and enriching experience, the virtual lab considers the following aspect for the instruction of fluid power components: hand-on experience, fluid flow visualization, and, most importantly, a safe, well-controlled experience.

The success of a virtual environment relies on the application–user interaction. The user interface is designed to select the practices to perform by using buttons to change between scenes. These buttons also enable the practice, reset, and placement of some clues to complete the task, as seen in figure 6.d.

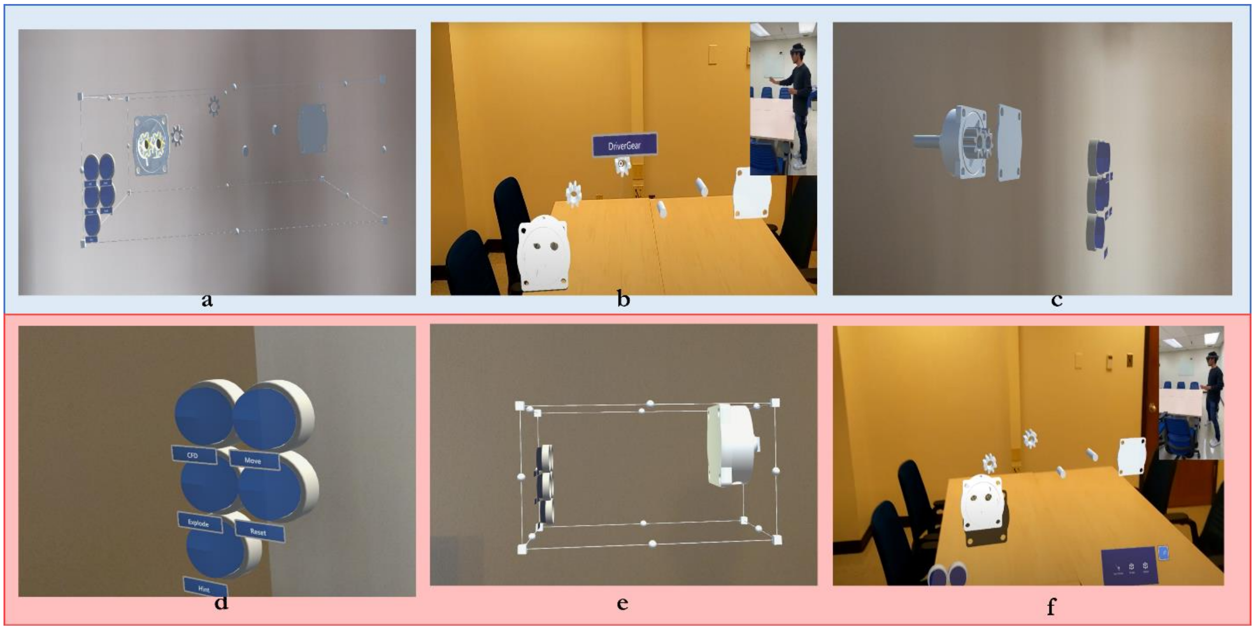


Figure 6. Mode 1 - assembling process. a) repositioning and scaling of the Gear Pump. b) Labels for each individual component. c) Gear Pump Assembled. d) user interface, buttons to reset the app or switch the mode. e) explode view of the Gear Pump. f) reset mode.

The first step of this virtual application shows an exploded view of the gear pump, as seen in Figure 6.a. This shows students the different parts of this component. The main goal is to drag each component to the right place to assemble the pump. Before undertaking this task, the user should reposition the gear pump housing and scale it at their convenience. To guide the user in this mode, labels facilitate this process, as seen in Figure 6.b. For instance, when the user points at one of the pieces to assemble, they can see the name of that piece. This feature helps students identify the parts and the correct order to assemble the components. After completion, the gear pump can be reset to repeat the process. As shown in Figure 6.f., hints are shown in black boxes that help students with the assembly process. This feature can be activated or deactivated by the users to suit their skills.

The second task for this virtual lab is to familiarize the student with physical magnitudes. For example, the user can set the torque value, which is a force times distance that causes the gear to move. Thus, the student can control how much torque is exerted and instantly see changes in the gear's rotational speed.

As for the third module, the flow deployment, the user is presented with two different scenes; one represents the velocity fields where streamlines indicate the direction taken by the flow. The second scenario displays the pressure fields, revealing insightful patterns (e.g., high-pressure zone) in the operation of the pump. The user can also understand gear pump performance by measuring flow variables at specific key points, the – inlet and outlet ports.

The XR Gear Pump is intended to have three modes: component identification and assembly, fluid flow visualization, and dynamic interaction between the gears. When designing the virtual laboratory, key variables were defined from the hardware and implemented in the software environment. The authors designed the virtual laboratory for HoloLens 2 from Microsoft and programmed it in Unity. The latter was selected because it is a well-documented platform to program virtual reality environments and is widely used in the video game industry. Unity includes standard tools for the creation of VR environments. For example, scripts for assembling game objects (3D models), physics simulation, and a basic user interface. However, for this application, new scripts were needed. Consequently, scripts for moving through different modes, accounting for the movement of the gears, and user interfaces to distinguish other fluid flow fields were designed. Prefab objects were used within the user interface, but buttons were added in a customized script to separate the velocity from the pressure field scene. The scripting process was conducted by C#, a programing language supported in Visual Studio 2019. This platform allows for the deployment of the virtual app to the HoloLens 2, as shown in Figure 3.

6) Preliminary testing results from survey

Preliminary survey testing was completed before implementing the XR labs into an advanced fluid power course. Future implementations of the labs will take place during the regular scheduled laboratories in the academic semester. Two laboratory experiences will be integrated into the course and assessed by obtaining the students' perceptions of the XR technology. The overall goal of this research is to improve student understanding of fluid power components and systems by developing immersive visualization tools.

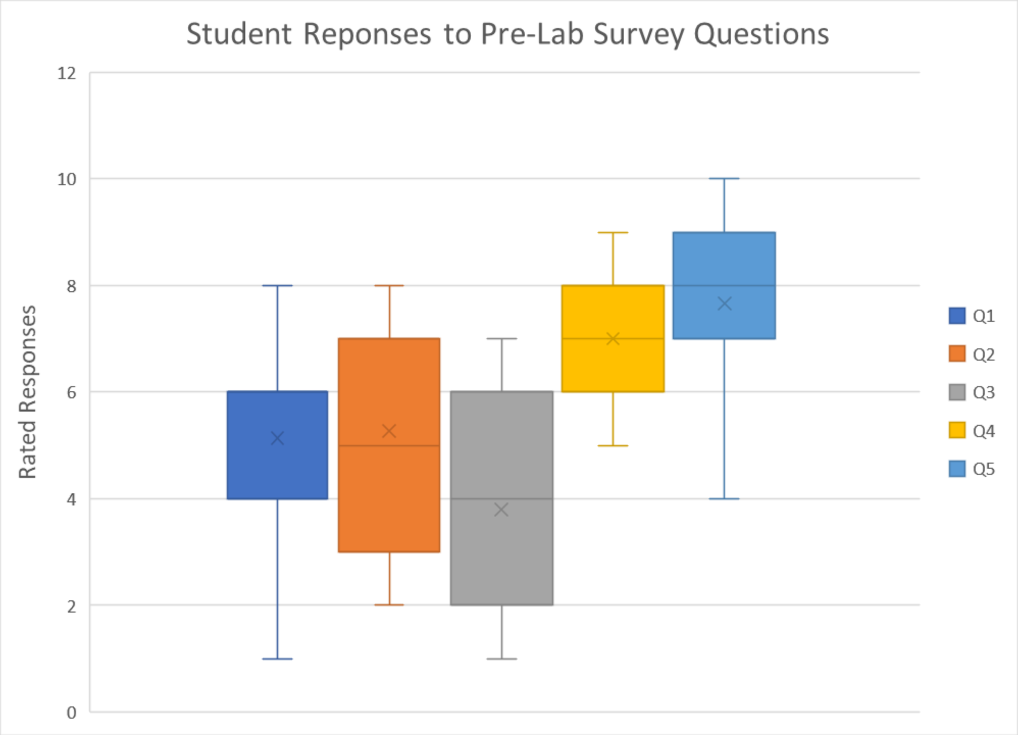


Figure 7. Student responses to gear pump pre-lab survey questions.

Analysis of the laboratory responses after the implementation of this laboratory will be carried out using a similar method to previous mixed reality research [26]. In this study, students were asked to answer questions based on any previous experience with virtual/mixed reality and their perception on its effectiveness as an educational tool. Both of the laboratories (gear pump and relief valve) tested contain a pre-lab and post-lab questionnaire measuring their perceived value of the XR laboratories. At the present moment, this paper reports the results obtained from the pre-lab survey. The responses are quantified with numerical results using a Likert scale survey (the survey questions are presented in the appendix). Additionally, a second post-lab questionnaire will be used to get free response feedback. The general results of the pre-lab survey are shown in figure 7. Pre-lab survey questions are denoted on the table below as "Q" followed by the question number (i.e., Question 1 = Q1).

Statistics from preliminary data collection of the gear pump lab exercise evaluated the responses of 15 students. Responses to the gear pump pre-lab survey (figure 7) were used to interpret the typical knowledge level and level of comfort with gear pumps among advanced fluid power students. Data collected suggests a medium level of understanding of gear pumps (figure 8). This is known from the 33% of students who answered a confidence level of six out of ten, and about 60% of the students considered reported that their confidence was 6 or less on a 10 point scale. The sample mean being a confidence rating of 5.13 on the Likert scale from 1-10, where one means no confidence and ten means very confident. A larger interquartile range (IQR) was seen in student understanding of how fluids move through a gear pump (figure 9). A similar variation in responses and a similar average of 5.27 compared to the previous question, suggests that at least one cause to the lack of student gear pump knowledge is not understanding fluid circulation through the pump.

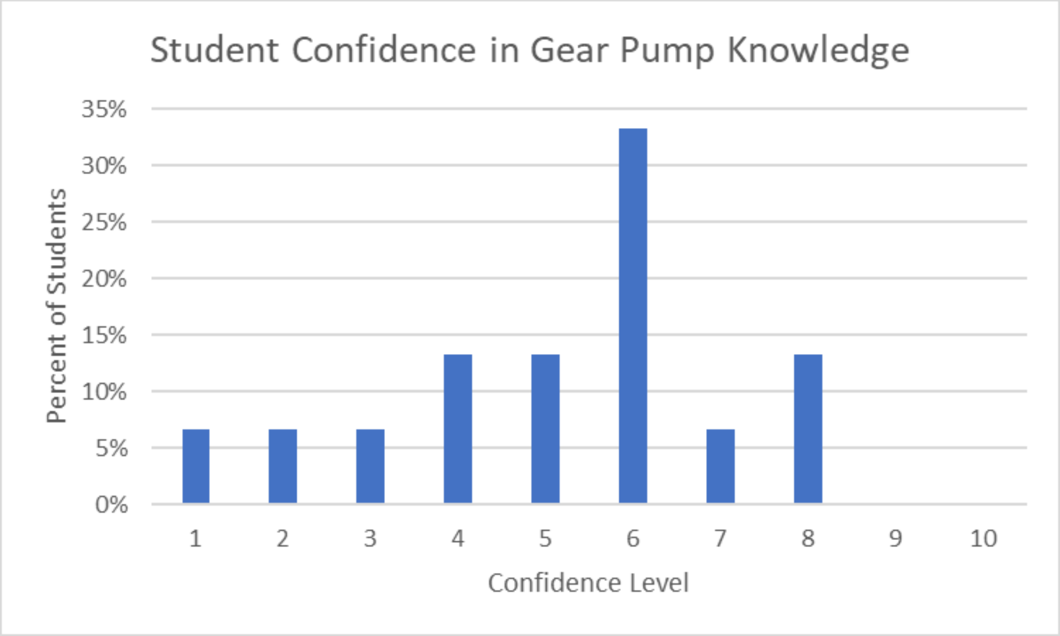


Figure 8. Reported student confidence in Gear Pump knowledge.

An even distribution was seen among student experience levels with XR (figure 10). Experience level in this question refers to a self assessment by the students of their past experiences with using XR devices. With an average experience level of 3.80/10, students within the fluid power course were considered to be low in their experience with XR. Past research has shown that students with little to no experience with XR have benefitted more from XR in education than students with higher levels of past XR experience. It stands to reason that a marked improvement in understanding fluid circulation through XR environments should be seen during post-lab survey analysis [24].

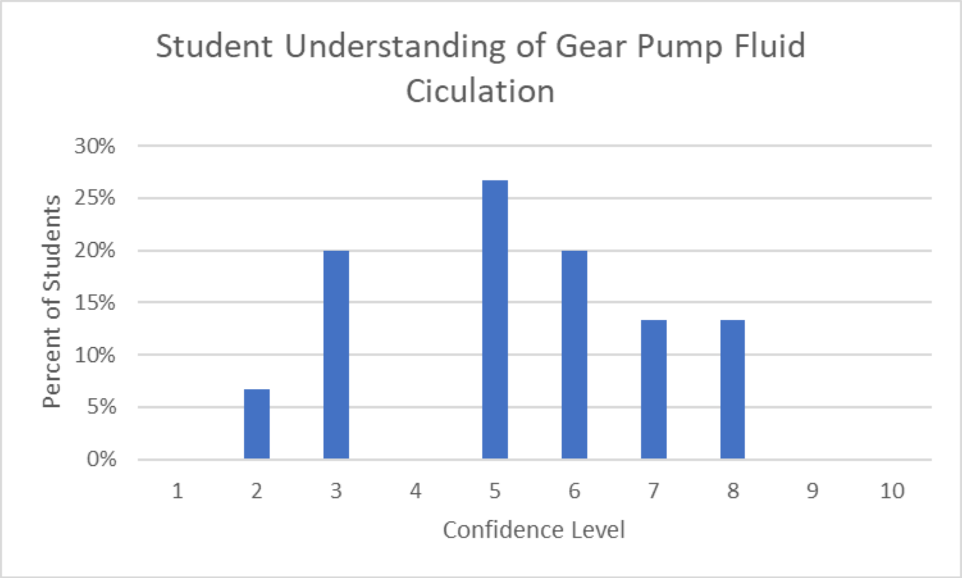


Figure 9. Reported student understanding of fluid circulation through a Gear Pump.

Figure 10. Student experience levels with Extended Reality.

Using XR within the fluid power classroom was received well among the surveyed students, with 90% of the responses within the 70-90% preference for the use of XR in the laboratory, levels 7-9 (figure 11).

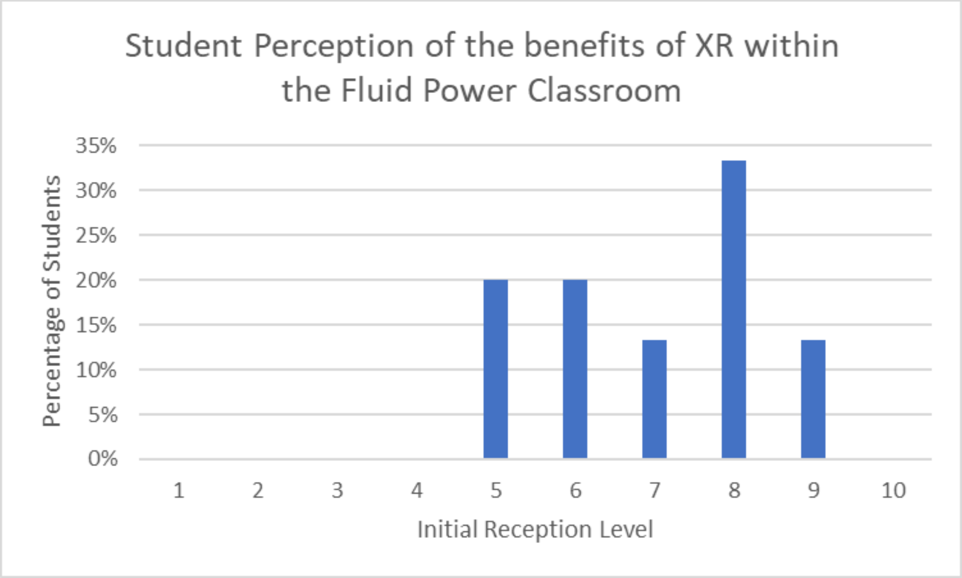


Figure 11. Initial student reception levels of XR used within the fluid power classroom.

When asked about their preference to physical interactions with components vs. an augmented interaction (figure 12), 90% of the responses were within 70-100% preferred physical interaction, levels 7-10.

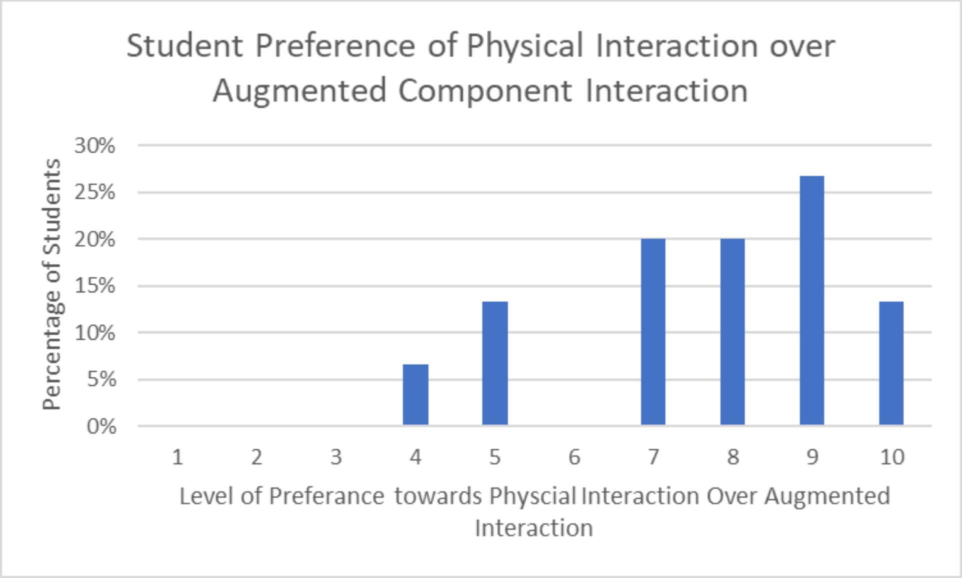


Figure 12. Initial student preference towards physical interaction of components vs. augmented interaction of components.

7) Conclusion and future work

Surveyed students in an advanced fluid power course showed only a medium level of confidence in their understanding and comfortability with gear pumps. Fluid circulation through a gear pump showed a similar level of confidence. Extended reality was perceived by the students as a viable alternative to their traditional fluid power laboratories. However, student preference leaned strongly towards physical interaction with components as opposed to augmented interaction. The use of CFDs within XR laboratories is expected to play a major role in student comprehension and comfortability with gear pumps. Changes in gear pump comprehension among advanced fluid power will be reassessed after the culmination of the XR gear pump lab. Future work will include the implementation and analysis of an XR relief valve laboratory.

8) References

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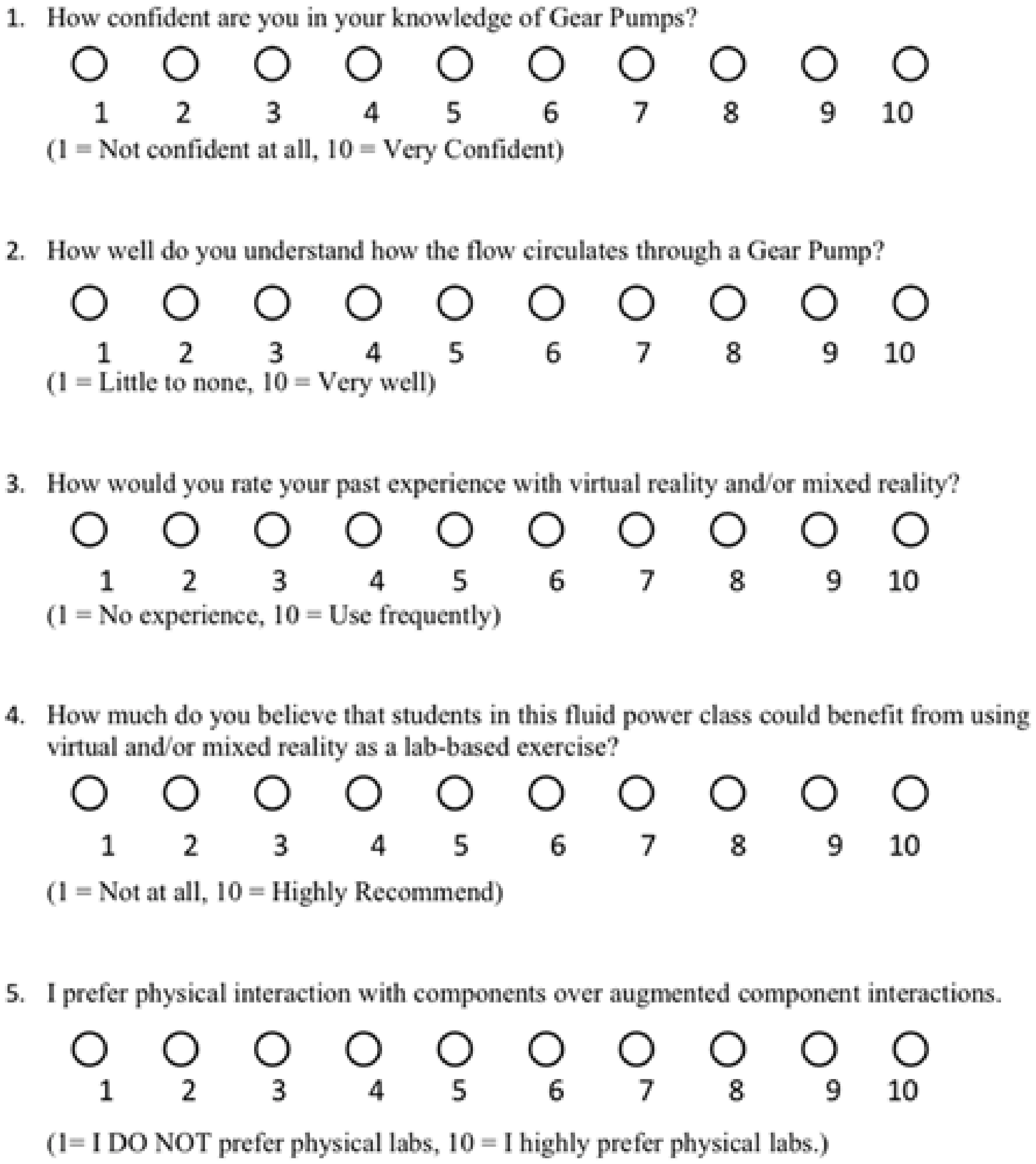
Appendix

A. Gear Pump pre-lab/post-lab survey questions.



1. How confident are you in your knowledge of Gear Pumps?

○	○	○	○	○	○	○	○	○	○
1	2	3	4	5	6	7	8	9	10

(1 = Not confident at all, 10 = Very Confident)

2. How well do you understand how the flow circulates through a Gear Pump?

○	○	○	○	○	○	○	○	○	○
1	2	3	4	5	6	7	8	9	10

(1 = Little to none, 10 = Very well)

3. How would you rate your past experience with virtual reality and/or mixed reality?

○	○	○	○	○	○	○	○	○	○
1	2	3	4	5	6	7	8	9	10

(1 = No experience, 10 = Use frequently)

4. How much do you believe that students in this fluid power class could benefit from using virtual and/or mixed reality as a lab-based exercise?

○	○	○	○	○	○	○	○	○	○
1	2	3	4	5	6	7	8	9	10

(1 = Not at all, 10 = Highly Recommend)

5. I prefer physical interaction with components over augmented component interactions.

○	○	○	○	○	○	○	○	○	○
1	2	3	4	5	6	7	8	9	10

(1= I DO NOT prefer physical labs, 10 = I highly prefer physical labs.)