

Article

Virtual Reality in Fluid Power Education: Impact on Students' Perceived Learning Experience and Engagement

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Abstract: The significance of practical experience and visualization in the fluid power discipline, highly tied to students' success, requires integrating immersive pedagogical tools for enhanced course delivery, offering real-life industry simulation. This study investigates the impact of using virtual reality (VR) technology as an instructional tool on the learning and engagement of 48 mechanical engineering technology (MET) students registered in the MET: 230 Fluid Power course at Purdue University. An interactive VR module on hydraulic grippers was developed utilizing the constructivist learning theory for MET: 230 labs, enabling MET students to explore light- and heavy-duty gripper designs and operation through assembly, disassembly, and testing in a virtual construction environment. A survey consisting of a Likert scale and short-answer questions was designed based on the study's objective to evaluate the students' engagement and perceived attitude toward the module. Statistical and natural language processing (NLP) analyses were conducted on the students' responses. The statistical analysis results revealed that 97% of the students expressed increased excitement, over 90% reported higher engagement, and 87% found the VR lab realistic and practical. The NLP analysis highlighted positive themes such as "engagement", "valuable experience", "hands-on learning", and "understanding", with over 80% of students endorsing these sentiments. These findings will contribute to future efforts aimed at improving fluid power learning through immersive digital reality technologies, while also exploring alternative approaches for individuals encountering challenges with such technologies.

Keywords: virtual reality; engagement; learning; fluid power; hydraulically actuated; immersive

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1. Introduction

Fluid power is a specialized study area in mechanical engineering (ME) and mechanical engineering technology (MET) programs. It has well-defined research and scholarly activities, serving diverse industries such as agriculture, construction, transportation, aerospace, marine, manufacturing, and many other sectors that demand high power densities [1]. Fluid power education involves fluid dynamics, hydraulics, pneumatics, and motion control systems [2], many of which expose students to machinery and systems research [3–6]. Students are expected to attain learning outcomes centered on designing and implementing fluid power circuits, studying and visualizing mechanical actuation and control, and conducting computational fluid dynamics simulations to evaluate and predict the behavior of systems.

Given the learning outcomes and hands-on nature of fluid power systems, fluid power education significantly utilizes constructivist learning theory, requiring students to actively construct their knowledge through experiential processes [7]. The constructivist learning theory, or constructivism, is an epistemology based on observation and scientific study to explain how people learn and acquire knowledge in specific fields [7,8]. This theory defines

learning as a constructive process in which learners acquire knowledge by developing an internal illustration of experience [9,10]. It adopts the idea that human learning is constructed with time, where learners develop their new learning based on the foundation of their previous understanding [11]. Hence, learners actively participate in their learning, constructing their knowledge and understanding based on their experiences [10]. So, as learners perceive new experiences, they continuously upgrade their mental models to reflect further information, which allows them to build their interpretation of reality [12–15]. Learners perceive experiences through various reception channels, e.g., visualizing and hearing, reflecting and acting, reasoning logically and intuitively, memorizing, and engaging in hands-on or practical experiences [16]. Among these approaches, visualization and engagement in practical activities receive significant attention in constructive learning within fluid power education [17]. This is due to their ability to engage students and support them in constructing large and intricate information structures, making them more understandable [18,19].

The significance of visualization and practical experience on students' learning in fluid power education calls for exploring visual pedagogical instruction methods, like using Virtual Reality (VR) Technology as a learning tool. VR is a high-tech multimedia visualization technology that integrates hardware and software to generate fully computer-simulated experiences to extend users with an immersive digital experience [20,21]. It immerses users in a computer-generated world using smart-wear techs like tech togs, headsets, skin electronics, and many other wearable technologies in which everything is digitized [22,23]. Such head-worn technology allows the user to achieve a sense of presence and immersion by creating a realistic, believable experience that tricks the user's senses into thinking of being immersed and surrounded by that environment [24].

Despite its capabilities, VR technology faces technical challenges and limitations related to real-time fidelity, image integration/quality, and motion sickness [25–27]. Real-time fidelity in virtual environments depends on timely feedback and the robustness of digital representations within the VR context. The complexity of algorithms responsible for rendering realistic digital objects in VR settings affects the time required to generate desired images. Additionally, issues with image integration and quality pose significant challenges in image recognition and retrieval within VR [27,28]. Moreover, prolonged exposure to VR environments (more than 10 min) commonly leads to motion sickness and discomfort, though the threshold for what constitutes a "long time" varies among users. Symptoms of motion sickness, including headaches, nausea, eyestrain, and disorientation, can vary significantly among individuals [29]. However, with all its features, and regardless of the technical limitations, VR technology is considered a promising tool for engaging students in an immersive virtual environment mimicking real-life industry settings. VR technology has the potential to transform fluid power education by providing a richer context and allowing for more realistic situations than students can experience in a classroom or laboratory setting.

Thus, this work investigates the impact of incorporating VR learning modules on students' learning and engagement, providing insights into the potential of VR technology in transmitting fluid power education. For the study, an interactive VR module on hydraulically actuated grippers was developed as a proof-of-concept relying on constructive learning theory and implemented in the MET: 230 laboratories offered by the School of Engineering Technology (SOET) at Purdue University. Qualitative and quantitative data were collected and analyzed through a survey developed by the research team to measure students' engagement while assessing their overall learning. The following research questions guide the conducted study:

RQ1: *How does incorporating VR modules affect the students' fluid power learning experience?*

RQ2: *How does the immersive nature of VR technology impact students' engagement in fluid power labs?*

RQ1 aims to explore students' perceptions of their learning experience, examining their attitudes toward the clarity and overall impact of the educational content. However, RQ2 focuses on studying students' perceptions of their engagement, investigating how actively involved and motivated they feel during the learning process. Addressing both research questions allows for a comprehensive understanding of both the educational outcomes and the level of student participation and enthusiasm.

The rest of this paper is structured as follows. Section 2 provides an overview of the utilization of VR technology as an effective pedagogical tool across diverse educational fields. This section introduces the widely used educational virtual environment taxonomy, and the practical applications of these environments in education are explored. Section 3 presents the conducted research study, showing the project execution, i.e., the developmental stages of the VR module, the formulation of the experimental design, data collection tools, and the data analysis tools. Section 4 provides a discussion of the research results. Finally, the paper concludes with Section 5, summarizing the essential findings and insights from the work.

2. Education in the Era of Virtual Reality

VR provides users with a safe, immersive, and realistic experience by transporting them into a three-dimensional (3D) simulated environment, effectively disconnecting them from the physical world [30]. The immersive nature of VR enables addressing issues associated with two-dimensional (2D) interfaces, such as the limited depth perception and impractical input control experienced within 2D settings [31–33]. The VR's immersive nature creates a sense of physical presence in the artificially generated world, allowing users to interact and engage with digital elements in real time, improving depth perception and presence [32]. It enables the creation of virtual replicas that capture all the properties/characteristics of the actual physical environments, ensuring the safe testing/execution of tasks/activities within a virtual realm that simulates real-life scenarios.

With all these capabilities, VR has shifted from being perceived as a gaming tool to becoming an invaluable professional education and training tool in recent years [34,35]. VR's ability to safely replicate classrooms and laboratories to test real-life scenarios in the virtual realm has increased its educational taxonomy [36]. Educators have been adopting this immersive tool across a broad spectrum of academic areas, especially engineering and engineering technology, benefiting from its educational taxonomy to facilitate students' understanding and foster their engagement and motivation [37–39]. The following two subsections provide an overview of the virtual environments' taxonomy used for educational purposes. They also introduce recent advancements in VR applications within engineering and engineering technology education achieved by adopting this taxonomy.

2.1. Educational Virtual Environments Taxonomy

Researchers categorize educational virtual environments based on the desired learning outcomes and objectives [40]. They divide the educational virtual environments into three categories: (1) VR setting for acquiring and understanding concepts; (2) VR setting for applying the acquired knowledge in typical situations; (3) VR setting for applying the acquired knowledge in challenging situations [41]. This categorization is highly connected to the degree of immersion and presence within the settings and, thus, the requisite hardware specifications [40,41].

2.1.1. VR Setting for Acquiring and Understanding Concepts

This VR setting aims to support students in comprehending theoretical knowledge in a particular field of study, such as concepts, terminologies, processes, events, formulas, facts, rules, etc. This VR setting is considered the least immersive environment, as the acquirement of the associated learning outcomes does not require the full presence of the users [41]. It relies on typical 3D visualization to expose students to a virtual realm mimicking real-life scenarios. It is readily delivered through stereoscopic displays, like

PCs equipped with powerful graphics cards, 3D glasses, audio systems, and other input/output devices to be experienced on projection walls or 3D monitors [42–44]. Besides the 3D displays, motion capture/gesture recognition technologies are utilized to captivate and involve users effectively. Such VR settings have been excessively used in multiple educational fields, such as history [45–49], geography [50–52], anthropology [53], etc.

2.1.2. VR Setting for Applying the Acquired Knowledge in Typical Situations

This category aims to expose students to practical experience, allowing them to apply the acquired theoretical knowledge by engaging them in specific tasks/activities in a virtual realm that simulates typical real-world situations [41]. Unlike category one, the VR setting in this category is fully immersive as it requires the students' profound physical and mental presence. For this reason, such VR settings comprise immersive-based systems designed to replicate and simulate specific practical working environments. These systems include, but are not limited to, (a) immersive-mounted VR headsets, like Meta Quest, HTC Vive, HP Reverb, and others; (b) hand-gesture and muscle movement tracking devices, like Kinect, MYO control armband, Leap Motion control [54–56]; and (c) haptic suits, such as TESLASUIT Dev Kit, TactSuit Pakket, etc. [57,58]. Integrating such technologies enables the creation of a comprehensive, immersive learning environment, allowing students to practically engage with their academic content in a dynamic and realistic virtual space. Therefore, this category of VR settings is crucial for learning as it equips students with practical skills and critical thinking abilities necessary for success in their future careers.

2.1.3. VR Setting for Applying the Acquired Knowledge in Challenging Situations

This category allows students to engage in virtual practical situations to apply theoretical knowledge gained in class. However, the VR settings developed for this category focus on exposing students to more challenging critical situations within an immersive, safe, and secure environment [41]. They allow for replicating and simulating dangerous real-life scenarios that transcend the scope of conventional classroom lectures and laboratories [59]. Such risky scenarios involve intricate tasks, like synthesizing novel phenomena, formulating strategic action plans, and evaluating the situation based on specific criteria [60]. This category is considerably employed in medical sciences, engineering, and technology fields, requiring advanced and precise hands-on learning tools [61,62]. These tools are necessary to prepare students for real-world industrial situations by providing engaging and practical learning experiences. Thus, this category is also considered significant as category two, given its potential to expose students to critical career-life situations.

2.2. Educational VR Applications

As technology advances, integrating the educational virtual environment taxonomy plays a vital role in transforming the future of immersive and practical learning experiences across various educational fields. The three categories of educational virtual environment taxonomy have been used by many educators within various academic fields, from engineering [37–39,63,64] to applied science [65,66] and medicine [67–70], to assist students in acquiring basic concepts and engaging them in practical experience. Among many academic fields, engineering and engineering technology have significantly relied on virtual environments to develop VR simulators across various engineering disciplines.

Many educators in ME and MET adopted categories one and two of the educational virtual environment taxonomy to engage their students in robotics applications [38,71–75]. For instance, the two groups of researchers in [38,73] developed VR settings for their robotics labs based on category two to enable students to apply the theoretical concepts gained in the classroom to operate and control robotic arms.

Besides VR applications in robotics, few educators have been developing semi-immersive VR settings for fluid power education building on category one of the educational virtual environment taxonomy, as their learning environments were not fully immersive and aimed to assist students in acquiring fluid power concepts [76–78]. For instance, the

authors in [76] designed and implemented an educational VR application called the virtual hydraulic trainer to be incorporated into fluid power training. The virtual trainer is a computer-aided 3-dimensional (3D) interface accessible through a computer desktop. It includes 3D models and simulations for multiple systems to provide an interactive and engaging learning experience. The trainer was incorporated and evaluated in fluid power courses. Although it was not fully immersive, the results showed it effectively enhanced the learning experience and understanding of power system principles. Another semi-immersive computer-aided virtual trainer was designed in [77,78]. This virtual trainer offers students a dynamic interactive learning environment, supporting them in acquiring fluid power principles and fundamentals.

To this end, and based on the provided literature, VR for fluid power learning and engagement is still not fully incorporated and has not been thoroughly investigated. Most of the VR settings developed are limited and not fully immersive, lacking the ability to immerse students in virtual environments mimicking real-life industry settings. Therefore, this work aims to study the impact of incorporating an interactive VR experience as a learning tool on students' learning and engagement to improve the teaching curricula for fluid power courses.

3. Research Study

An institutional review board (IRB) approval was obtained to design and incorporate an interactive VR module into the MET: 230 Fluid Power laboratory at Purdue University. The goal was to examine the effectiveness of VR in improving students' learning and engagement. The following subsections provide an overview of the VR module development and introduce the designed survey and experimental design and the adopted evaluation methodology for analyzing the collected data.

3.1. Interactive VR Module Development

The module's VR environment was designed explicitly for MET students enrolled in fluid power courses relying on category two of the education virtual environment taxonomy (designing an interactive VR setting to apply theoretical knowledge through engaging tasks in a virtual realm simulating real-world situations). The module was developed following the principles of the constructive learning theory, aiming to engage students in active participation in fluid power education. This approach encourages students to build on their existing knowledge to deepen their understanding of new concepts and ideas. The module introduces students to the design and operation of mechanical and hydraulic subsystems of hydraulically actuated grippers. It enables students to construct knowledge about gripper design through hands-on experiences and interactions with VR digital copies of the gripper designs, rather than passively absorbing information. Students will apply their existing knowledge of hydraulic systems as a foundation to build on their new information related to hydraulic grippers by engaging in fluid power hands-on tasks/activities within the VR module. Such activities involve assembling and disassembling different hydraulic gripper designs and testing their mechanisms within an interactive VR setting that mimics real-life situations.

Hydraulically actuated grippers are highly coupled complex systems comprising hydraulic and mechanical units like pumps, motors, hydraulic actuators, valves, etc. The complexity of the utilized units and their corresponding mechanisms makes understanding the grippers' operation challenging. Thus, digital representations of hydraulically actuated gripper designs were created in a spatial interactive VR environment. The dynamic VR copies of the grippers' designs were developed using the Oculus Virtual Reality (OVR) Toolkit [79] and Metrics Tool [80] for Unity, a Steam VR Overlay utility. The execution of the VR module comprised three main phases (Mechanical Design, VR Setup and Development, and Technical Testing), illustrated in Figure 1.

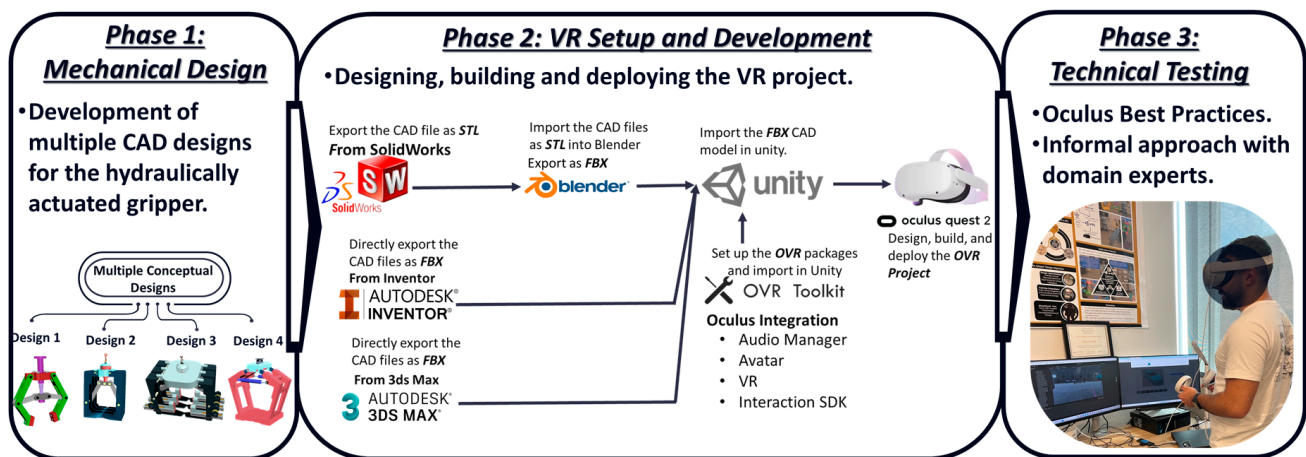


Figure 1. Diagram showing the three phases of the VR project execution.

3.1.1. Phase 1: Mechanical Design

Phase 1 focused on designing conceptual paradigms for the hydraulically actuated grippers to implement digital copies in a VR environment. Each of the generated designs comprised two subsystems: mechanical and hydraulic. The mechanical subsystem involved the structural model of the gripper, e.g., gear train, shafts, joints, flexible brackets, sliders, etc. The hydraulic subsystem consisted of the corresponding hydraulic circuit encompassing the hydraulic units and components, like the pump, motor, hydraulic actuators, valves, etc.

3.1.2. Phase 2: VR Setup and Development

Phase 2 focused on developing a virtual environment mimicking construction-like settings, designing virtual copies of the gripper models within the virtual environments, and conducting the scripting required for spatial interaction. To construct the VR environment, a kit with 50 unique realistic assets and prefab counterparts was used for heavy-load machines from the Unity asset store to engage students in a virtual realm simulating typical real-world situations. Our work in [81] provides a detailed explanation of the design and implementation of the environment. The developed gripper CAD designs were then built and deployed using the OVR Toolkit for Unity 2020.3.8 to visualize the designs in a VR environment. The CAD files generated in SOLIDWORKS were converted into FBX file format supported by Unity using Blender 4.1 Software. Then, the FBX data files involving the 3D components of the grippers were imported into Unity to set up the project. The imported assets (gripper's 3D components/animations) were positioned and organized in the required scene as Unity game objects to create and design the envisioned environment.

Then, the Oculus Integration software development kit (SDK) was downloaded from the Unity Asset Store and imported as Unity assets [82]. The Oculus Integration SDK package enabled advanced rendering, social, platform, audio, and avatar interaction for Oculus head-mounted displays. It involved many Oculus Integrations, like the audio manager, avatars, VR, interaction SDK, etc. After setting up the Oculus VR project, the OVR scripts (OVR Grabber, OVR Grabbable, etc.) were utilized and edited to grab and manipulate the gripper components and conduct the virtual assembly. Also, additional unity scripts were built and compiled using (UnityEngine), (UnityEngine.Events), (System.Collections), (System.Collections.Generic), (HoloToolkit.Unity.Buttons), etc., to allow for various types of interactions, spatial awareness, eye/hand tracking, and user interface (UI) controls. Figure 2 shows a section of the developed VR construction lab involving UI controls to visualize and interact with the grippers' components, showcasing two distinct virtual stations, each designated for one gripper. The UI controls offer students accessibility and control over the two stations, allowing the students to lock and unlock the stations as instructed in the module to complete the required tasks.



Figure 2. Section of the developed VR construction lab with the UI controls.

A virtual agent was also created to instruct and guide the user throughout the module, as the module design included providing clear guidance to students throughout their VR lab experience. Figure 3 shows the virtual agent standing in the corner to direct and assist the students while navigating the VR environment and assembling and operating the grippers.



Figure 3. The virtual avatar serves as a virtual agent for providing guidance and assistance through visual/audio instructions.

The avatar aimed to provide students with instructions, ensure consistent lab navigation and minimize potential confusion. Students were directed by the avatar to begin their tasks with Gripper 1 in Station 1, while Station 2 remained inaccessible. After completing tasks at Station 1, the avatar guided students to unlock and move to Station 2. This approach reinforces the learning process, enabling students to concentrate on the design and

tasks associated with each respective gripper. After adding all the required features, the project was deployed and installed on Meta Quest 2 to test the visualization and assembly of the gripper designs in a VR setting.

3.1.3. Phase 3: Technical Testing

During phase 3, the required cross-platform input system for VR interaction was tested based on the Oculus Best Practices guide [83,84]. Fundamental Oculus best practices were adopted while developing the module to ensure the content conforms to safety, comfort, and industry standards. This approach aimed to prevent any simulator sickness in students when engaging with the VR modules. The testing was conducted among the research members, all proficient in VR. This initial testing followed an informal approach with domain experts, similar to the protocol adopted in [85,86]. It focused on the module's technical aspects, including audio, visuals, and UI controls, to ensure the VR module adheres to Oculus Best Practices, thus making it safe for students to experience.

3.2. Experimental Design (Settings and Participants)

After developing, testing, and validating the VR module and survey, the module was incorporated into the MET: 230 fluid power laboratory at Purdue University. The module was experienced by all 48 students (8 females and 40 males) enrolled in the course at Lambertus Hall on the Purdue West Lafayette campus. All 48 students participated in the interactive VR module as part of their lab sessions. Therefore, the utilization of control groups was not possible, limiting the scope of the study, as it would have prevented a group of students from completing the required VR module tasks. The study was administered as shown in Figure 4.

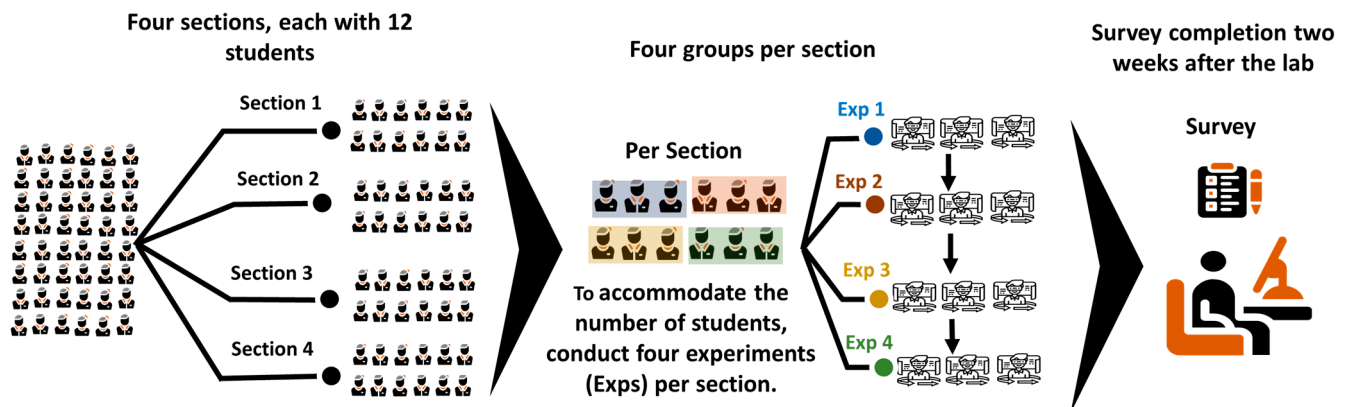


Figure 4. Diagram illustrating the adopted experimental design for conducting the study in the MET: 230 course.

Figure 4 shows that the 48 students were divided into four sections, each comprising 12 students. The total time to complete the VR module was 30 min, and the overall session time was two hours. To accommodate the number of students, the 12 students per section were divided into four groups, each comprising three students. This resulted in 16 groups of three students over the four sections. Subsequently, the study was conducted in 16 experiments over the four sections (four experiments were generated per section). In each experiment, three students experienced the VR module simultaneously but independently, i.e., each student in their own scene. Figure 5 shows three students per group within one of the sections experiencing the VR module, where each student had a setup comprising Lenovo Legion/Alienware gaming desktops, each connected to a VR headset.



Figure 5. VR Setup for conducting the research study.

After experiencing the VR module, the other three students in the following group were asked to start experiencing the module, including all its tasks and activities. This procedure has been consistently applied across all the other groups in the other sections, ensuring the participation of all students in completing the same module with all the tasks and facilitating study management and data collection. Then, two weeks after experiencing the VR module, all the students were asked to complete the survey. The adopted experimental design allowed for minimizing the influence of students' initial excitement about the VR technology on their responses, as students' responses must be more focused on the technical aspects of the module and its effects on their task performance rather than on their fascination with the technology itself. The surveys were completed through BrightSpace, an online course management platform. Brightspace was used throughout the study to import the surveys and collect and manage the reports/data. After completing the surveys, unique identifiers were assigned so that the students' names were no longer included in the data.

3.3. Data Collection Tool

The data collection method utilized throughout the study involves a mix of quantitative and qualitative survey questions, as shown in Table 1. The survey consists of six Likert scale questions and four short-answer questions designed based on the study's objectives to provide answers to the research questions. The development of the short questionnaire used in this study involved a rigorous process to ensure its relevance and validity. Initially, the research team devised questions to capture students' perceptions of the VR module, focusing on technical and educational dimensions. These questions underwent several iterations, informed by feedback from experts in VR, fluid power education, and data analytics. The decision to develop a questionnaire was driven by the research's specific requirements, which were not adequately addressed by existing instruments. Specifically, existing instruments generally focus on broader aspects of educational technology that do not align with the specifics of fluid power systems and VR applications.

Table 1. The developed survey questions.

#	QUESTIONS
LIKERT SCALE QUESTIONS	
Q1	While conducting the VR activity, I felt the presence and depth.
Q2	I was immersed in the VR environment.
Q3	The VR environment helped me focus on the activities (Gripper Assembly/Mechanism Testing)
Q4	This VR experience increased my interest in learning about assembly/disassembly processes.
Q5	This VR activity made learning feel much more exciting and enjoyable.
Q6	This VR lab felt more practical and realistic, mimicking real-industry life settings.
SHORT-ANSWER QUESTIONS	
Q7	What did you like most in today's lab?
Q8	What did you like least in today's lab?
Q9	What engineering design decisions can such a module aid you in?
Q10	Was the experience valuable to you? If so, how? If not, why?

The data acquired by the Likert scale questions are based on the 1 to 5 bipolar scale rating (5: Strongly Agree, 4: Agree, 3: Neither Nor, 2: Disagree, and 1: Strongly Disagree) and thus can be analyzed by descriptive statistical analysis. These questions were designed by the research team to measure the students' attitudes toward the VR module from a technical and learning perspective and answer RQ1. For instance, Q1, Q2, and Q3 allow examining the technical aspects of the VR module by inspecting whether the VR experience achieved some of the basic OVR standards, such as immersive quality, presence/depth, user interface, and more. The remaining Likert scale questions (Q4, Q5, and Q6) enable for acquiring data regarding the module's applicability in improving the student's learning experience. Such questions aim to assess the understanding of aspects such as the enjoyment of the VR experience, its perceived value, and its ability to simulate real-life engineering settings. Besides the Likert scale questions, short-answer questions (Q7, Q8, Q9, and Q10) were designed to investigate various aspects of the problem. Q7 to Q10 aim to explore the impact of the VR learning experience on engagement, understanding of engineering concepts, and overall learning satisfaction, thus providing answers to RQ2. The short answer questions encourage students to provide factual and interpretive textual responses, minimizing biases and enabling a comprehensive analysis of their experiences.

The reliability and consistency of the Likert scale questions were validated by conducting a reliability test. Two key indicators were investigated, Cronbach's Alpha and Cronbach's Alpha Based on Standardized Items, which allowed measuring the consistency of the survey items' construct. Also, the entire survey was validated through a university review board comprising experts from VR, fluid power education fields, and data analytics. This board consisted of two VR specialists recognized for their work in extended reality (XR) development and affiliated with prominent XR firms, an expert in fluid power pedagogy and education, and a fourth expert skilled in data analytics, particularly in NLP analysis. These individuals are highly regarded for their expertise in their respective fields.

3.4. Data Analysis Methods

Qualitative and quantitative analyses were generated to examine the acquired data. For the quantitative analysis, a reliability test was conducted on the Likert scale questions (Q1 to Q6) using *Cronbach's Alpha* and *Cronbach's Alpha Based on Standardized Items* to study the questions' quality and test the degree of consistency and stability in the results. Then, after confirming the reliability of the chosen measurement tool, a descriptive analysis was carried out on the students' responses to the Likert scale questions. For this analysis, com-

prehensive analytics were performed using the Statistical Package for the Social Sciences (SPSS), a leading statistical software suite [87] to compute statistical metrics, including mean and standard deviation. Also, an inter-item correlation matrix was generated to explore and validate the correlation between the Likert scale responses.

For the qualitative analysis, thematic and sentimental analyses were generated to study the students' textual responses to questions (Q7 to Q10). The thematic analysis involved identifying recurring patterns and concepts coded and categorized to derive the most significant themes and their corresponding weights in the students' responses. NVIVO 1.7, a software package widely utilized in qualitative research, given its capabilities in coding and analyzing thematic data [85], was used to conduct thematic analysis. NVIVO's NLP was used to identify and generate the top significant words for each question. Then, themes were assigned for each question based on the top-generated words, and their corresponding weights were computed on NVIVO's NLP. In contrast, sentiment analysis measured the overall positive, negative, or neutral sentiments expressed in the student's responses. Sentiment analysis, known as opinion mining, is a subfield of NLP that involves identifying and extracting subjective information from source materials [88]. It aims to determine the overall sentiment or emotional tone behind a series of words to gain an understanding of the attitudes, opinions, and emotions expressed within the text [89]. This is a practical technique for analyzing survey responses, as it can provide insights into the respondents' feelings about the subject matter beyond what they explicitly state. For this study, the sentimental analysis was generated using NVIVO 1.7 by cross-referencing the themes, thus identifying recurring patterns or notable correlations. It identified the top 10 words associated with each question and provided the most prevalent sentiments expressed by the students. This analysis allowed us to investigate the data further and study the students' attitudes toward the VR module by providing insights into the respondents' perceptions and emotions regarding the subject matter. It allowed for achieving meaningful conclusions about the effectiveness of the VR module in enhancing learners' experience.

4. Results and Discussion

4.1. Reliability Test and Descriptive Analysis Results

The results of the reliability test conducted on the Likert scale questions show a Cronbach's Alpha $\alpha = 0.94$ and Cronbach's Alpha Based on Standardized Items $\alpha = 0.95$. Thus, Cronbach's Alpha values exceed 0.70, indicating that the survey items consistently measure the construct. These results show a high degree of internal consistency, indicating the internal consistency of the survey, thus ensuring the reliability of the adopted evaluation questions.

The findings of the descriptive analysis are reported in Table 2 and Figure 6. The results show that Q1 and Q2 had the highest means and lowest standard deviations ($M = 4.79$, $SD = 0.41$) and ($M = 4.65$, $SD = 0.48$), respectively. These results reveal that the students' responses to Q1 and Q2 (100% of the responses, as shown in Figure 6) ranged from "Agree" to "Strongly Agree". Similar to the results of Q1 and Q2, the results of Q3 ($M = 4.56$, $SD = 0.65$) reveal that 44 out of the 48 responses to Q3 were between "Agree" and "Strongly Agree", as visually shown in Figure 6. This proves the positive effect of the VR's immersive nature on improving the students' concentration while completing their assigned tasks, thus reinforcing their learning experience.

Table 2. Means and standard deviations for Likert scale questions.

Question	Mean (M)	Standard Deviation (SD)
Q1	4.79	0.41
Q2	4.65	0.48
Q3	4.56	0.65
Q4	4.48	0.58
Q5	4.69	0.51
Q6	4.31	0.75

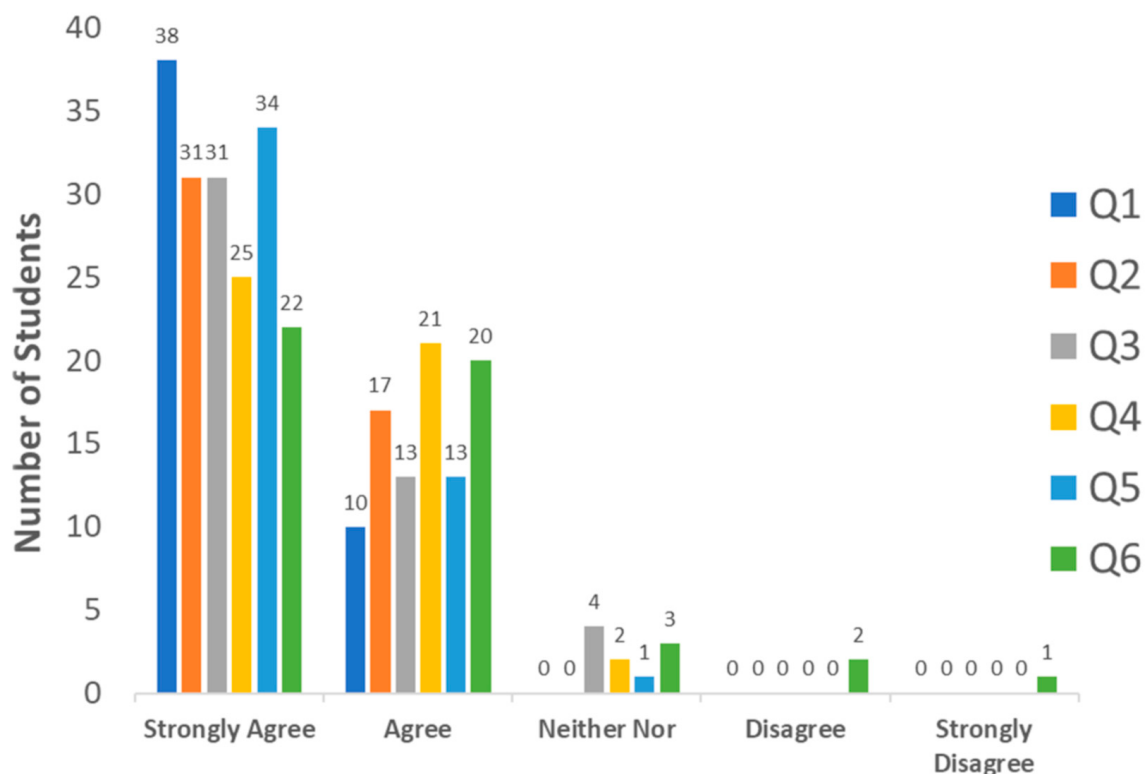


Figure 6. Statistical diagram illustrating the Likert scale data collected from the participants' responses to the six Likert scale questions.

Similarly, the students' responses to Q4 and Q5 resulted in ($M = 4.48$, $SD = 0.58$) and ($M = 4.69$, $SD = 0.51$), respectively, revealing that most of the students' responses (more than 45) to these questions ranged between "Strongly Agree" and "Agree". The results of Q4 and Q5 show that more than 93% of the students enjoyed learning about the grippers' assembly through VR. This demonstrates the effectiveness of the interactive features of the VR module in increasing students' interest in performing gripper assembly/disassembly and exploring the associated mechanisms. Consequently, it proves the potential of VR as a powerful pedagogical tool to enhance the overall engagement and enjoyment of the learning experience, as it allows students to construct their new knowledge through visualization channels.

Compared to the results of Q1, Q2, Q3, Q4, and Q5, the results of Q6 are marginally lower, with the lowest mean and highest standard deviation ($M = 4.31$, $SD = 0.75$). The analysis of responses to Q6 indicates that while most students provided positive feedback on Q6, it was not positive as observed in the preceding questions; more than 85% of the students had positive attitudes toward their perception of the VR lab as practical and realistic, and a few percent (6.25%) showed negative responses regarding the modules' practicality. The minimal percentage of reported negative responses requires further investigation by optimizing and refining the module to be more realistic, mimicking industry-like settings.

Therefore, the outcomes of the descriptive analysis show that most of the student's responses to all the Likert scale questions (more than 90%) were positive, ranging from "Agree" to "Strongly Agree". Such findings offer insights into the applicability of VR technology to enhance the students' learning experience in fluid power education. The results reveal that VR technology in the fluid power course actively engaged students in their learning process, enabling them to construct their knowledge over time. These results will contribute to future work to serve the students' pedagogy and learning more effectively and thus enrich their overall educational experience. However, it is important to note that the novelty of VR technology itself might have contributed to these positive responses. The

initial excitement and novelty effect could have influenced students' attitudes. Further studies should be conducted to assess the long-term impact of VR technology on learning outcomes once the novelty has worn off.

Besides the statistical metrics computations, the results of the inter-term correction matrix are reported in Table 3, indicating significant relationships among the students' responses. The comprehensive evaluation of the inter-item correlation matrix in Table 3 shows the degree of interdependence among the individual survey items, presenting the correlation (r) and p value for each correlation. The correlation with the highest magnitude is between Q2 and Q3 ($r(48) = 0.92$, $p < 0.001$), indicating a strong relation between the student's immersion in the VR environment and their ability to concentrate on tasks. However, the correlation with the lowest magnitude, albeit retaining statistical significance, is between Q1 and Q4 ($r(48) = 0.60$, $p < 0.001$). This correlation shows a comparatively weak relationship between the immersive nature of the VR environment and the students' interest in learning about the assembly/disassembly process of the gripper. Furthermore, there is a moderately strong correlation between Q3 and Q5 ($r(48) = 0.86$, $p < 0.001$), indicating that the immersive nature of the VR environment can substantially increase the students' enjoyment of learning and engagement, thereby motivating students throughout their academic pursuits.

Table 3. Inter-item correlation matrix for Likert scale responses ($N = 48$).

Question	Q1	Q2	Q3	Q4	Q5	Q6
Q1	1					
Q2	0.69	1				
Q3	0.77	0.92	1			
Q4	0.60	0.77	0.79	1		
Q5	0.80	0.83	0.86	0.73	1	
Q6	0.63	0.67	0.81	0.87	0.71	1

$N = 48$; One-tailed correlation at $p < 0.001$. The color legend indicates that green shows high correlation, while yellow signifies a low correlation

While statistically significant, the correlation between Q6 and the other questions shows a moderate relationship between the module's applicability in mimicking real-life application settings, the immersive nature of the VR environment, and students' engagement and learning experience. For instance, the correlation between Q1 and Q6 ($r(48) = 0.63$, $p < 0.001$) indicates a moderate relationship between the practical and realistic nature of the environment and its ability to enhance the student's perception of presence and depth within the VR setting. Unlike the correlation between Q1 and Q6, the correlation between Q4 and Q6 is moderately strong ($r(48) = 0.87$, $p < 0.001$). This indicates a strong connection between the students' interest in learning about the assembly/disassembly process and their perception of the VR lab as practical and realistic. These findings emphasize the significance of the VR environment in mimicking real-life settings, which positively affects students' engagement by reinforcing their learning experience.

4.2. Thematic and Sentimental Analysis Results

4.2.1. Results and Key Themes of Thematic Analysis

Table 4 shows the results of the thematic analysis, i.e., the systematically quantified themes from the students' responses to the four short-answer questions (Q7, Q8, Q9, and Q10) generated using NVIVO's NLP. The most prevalent themes generated for Q7 were the "virtual reality experience" (31.24%), followed by "hands-on learning" (27.20%), "learning about grippers" (23.47%), and "engaging environment" (18.09%). These themes indicate that students had positive attitudes toward the immersive and interactive nature of the VR module, the practical aspect of assembling the grippers, and the lab environment's educational value and engaging nature. The generated themes reveal VR's applicability and effectiveness in engaging the students in their learning process, making them actively construct their new knowledge based on their existing information. For Q8, the top

generated themes were “motion sickness” (42.61%), “confusion and difficulty” (26.49%), “technical issues” (24.95%), and “No negative experiences” (5.95%). These themes show that the negative aspects of the VR experience included experiencing physical discomfort while using VR, adding challenges in understanding the laboratory instructions. This highlights VR’s limitations in terms of causing discomfort to some users who are not familiar with digital technologies, all of which might affect their experience. The limitation of motion sickness in VR is a common issue reported in numerous studies [25–28]. Research studies reveal that prolonged exposure to VR environments (over 10 min) will cause motion sickness and discomfort, as around 80% of individuals exposed to VR experience motion sickness within the first 10 min of exposure [29,90]. The issue of motion sickness is attributed to the technical issues associated with VR technology related to real-time fidelity, image stability, and image integration/quality [25–28].

Table 4. Thematic analysis of data acquired from the four short-answer questions (generate themes and corresponding weights).

Question	Theme	Theme Weight
Q7	Virtual reality experience	31.24%
	Hands-on learning	27.20%
	Learning about grippers	23.47%
	Engaging environment	18.09%
Q8	Motion sickness	42.61%
	Confusion and difficulty	26.49%
	Technical issues	24.95%
	No negative experiences	5.95%
Q9	Visualization and prototyping	40.61%
	Practical application and real-world environment	37.74%
	Understanding assembly and design	21.65%
Q10	Valuable learning experience	50.00%
	Understanding of grippers	22.16%
	VR technology experience	24.05%
	Negative experiences	3.78%

Our module was developed following Oculus best practices, as illustrated in Section 3.1, which helped minimize discomfort, allowing students to experience the module for 20 to 30 min. However, for a more effective reduction in motion sickness and future work, we recommend utilizing the state-of-the-art Mixed Reality (MR) technology. MR is an extension of Augmented Reality (AR) and VR, merging the physical world with a predesigned virtual environment through seamless human-computer interaction, providing a hybrid experience that blends real-world and virtual elements [91–94]. MR technology aims to address VR-related issues, particularly motion sickness.

Besides Q7 and Q8, the results of Q9 reveal that students perceived the module as beneficial for “visualization and prototyping” (40.61%), “practical application and real-world environment” (37.74%), and “understanding assembly and design” (21.65%). These themes indicate that students value the module’s potential to assist in visualizing and prototyping designs, applying their existing knowledge in practical and real-world contexts to construct their new understanding of assembly and design processes. Finally, the findings of Q10 show that 50% of the students found the experience to be a “valuable learning experience” (50%). Half of the students liked and valued the use of VR as a pedagogical tool for teaching the gripper’s design and operation. However, a minimal percentage (3.78%) did not find the experience valuable due to VR-associated issues like motion sickness, discomfort, and dizziness.

4.2.2. Results and Interpretations of Sentiment Analysis

The results of the sentimental analysis are reported in Table 5. The sentiment for Q7 includes words like “fun”, “immersive”, “hand-on”, etc., indicating that the students expressed enjoyment and had positive attitudes toward the interactive and immersive nature of the VR lab. Students found the hands-on experience of assembling the hydraulic grippers engaging and beneficial for their learning. The sentiment for Q8 is negative, as expected, given the nature of the question. It involves negative words like “sick”, “dizzy”, “hard”, and “glitches”, indicating feelings of physical discomfort (motion sickness, dizziness), technical glitches, and initial confusion with the VR system. Furthermore, the sentiment of Q9 involves words with positive meanings, like “work”, “aid”, “design”, and “help”, showing the students’ positive feedback toward the VR lab in aiding design decisions, particularly in terms of understanding assembly processes, visualizing the scale and interaction of components, and identifying potential design problems. Finally, the sentiments resulting from Q10 are considerably positive, as they involve the words “yes”, “works”, “help”, etc. This shows that students had positive attitudes toward utilizing VR for teaching, specifically toward the immersive nature of the VR environment and its effect on improving their engagement and learning experience. While the analysis of open-ended responses indicates that many students expressed positive attitudes toward utilizing VR, it is important to note that these findings are based on qualitative data. Therefore, these insights should be considered indicative rather than representative of the entire student group.

Table 5. Sentiment analysis: top 10 words generated per question.

Question	Top 10 Words
Q7	assemble, gripper, experience, learning, VR, components, environment, fun, hands-on, immersive
Q8	sick, VR, motion, dizzy, time, feel, controls, fast, glitches, hard
Q9	assembly, design, help, gripper, parts, product, aid, real, work, 3D
Q10	yes, experience, gripper, valuable, assembly, help, learning, use, understand, works

5. Conclusions

This work explored the impact of utilizing VR technology as a pedagogical tool in fluid power learning to expose students to practical experiences. An interactive VR module on hydraulically actuated grippers’ designs and operations was developed based on category two of the educational virtual environments’ taxonomy (applying theoretical knowledge in typical situations) and following the principles of the constructivist learning theory. The module was then incorporated into the MET: 230 fluid power course laboratory at Purdue University, and data was collected from 48 students who had registered for the course. A survey of six Likert scale questions and four short-answer questions was designed based on the study’s objectives to inspect the students’ perceived learning of the grippers’ designs and their attitudes toward the VR module. The developed data collection tool was validated using a reliability test and through the university review board. The acquired data was analyzed using quantitative statistical methods, and the short-answer questions data was analyzed using qualitative NLP analysis techniques, specifically thematic and sentimental analysis.

The findings answered RQ1 and RQ2, revealing the module’s applicability in increasing the students’ interests and engagement, allowing students to construct their new knowledge through their experience in the VR realm. Students’ responses to the Likert scale questions were positive, ranging between “4: Agree” and “5: Strongly Agree.” 100% of the students reported that the module was immersive, more than 90% claimed that the VR module was engaging, and 97% revealed that the lab was exciting. Also, around

87% indicated that the VR construction lab felt realistic and practical. Besides the descriptive analysis, the NLP analysis generated positive themes involving “engagement”, “valuable experience”, “hands-on learning”, and “understanding”. Themes emphasizing “engagement” and “valuable experience” surpassed 80%, revealing that over 80% of the students found the lab engaging and valued the VR learning experience. These findings provide insights into the impact of immersive XR experiences, like VR, on student learning and engagement in fluid power courses, making students take significant roles in their learning process. It proves the potential of such technologies to improve students’ learning and understanding of real-life situations that mimic engineering tasks in an industry-like setting. The results also reveal that despite VR’s positive impact on students’ learning and engagement, it has some limitations associated with causing discomfort. Approximately 42% of the students reported motion sickness and dizziness. Motion sickness is a common issue in VR technology and cannot be completely eliminated.

Additionally, while the positive feedback towards using VR in students’ learning experience is promising, it is indicative primarily of students’ initial perceptions and engagement rather than a comprehensive assessment of educational effectiveness. This study provides valuable insights into the efficacy of our VR application, but more data can be collected that captures the student’s learning rather than their perceived learning. Specifically, collecting more finely-grained qualitative data, such as students’ learning logs, post-questionnaire follow-up interviews, and focus group sessions, could have yielded more detailed findings. Future research will incorporate these methods to enhance the robustness and depth of the findings, thereby informing better practice in VR application design and implementation.

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