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A Utility Framework for Selecting Immersive Interactive Capability and Technology for Virtual Laboratories

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A UTILITY FRAMEWORK FOR SELECTING IMMERSIVE INTERACTIVE CAPABILITY AND TECHNOLOGY FOR VIRTUAL LABORATORIES

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ABSTRACT

A UTILITY FRAMEWORK FOR SELECTING IMMERSIVE INTERACTIVE CAPABILITY AND TECHNOLOGY FOR VIRTUAL LABORATORIES

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There has been an increase in the use of virtual reality (VR) technology in the education community since VR is emerging as a potent educational tool that offers students with a rich source of educational material and makes learning exciting and interactive. With a rise of popularity and market expansion in VR technology in the past few years, a variety of consumer VR electronics have boosted educators and researchers' interest in using these devices for practicing engineering and science laboratory experiments. However, little is known about how such devices may be well-suited for active learning in a laboratory environment. This research aims to address this gap by formulating a utility framework to help educators and decision-makers efficiently select a type of VR device that matches with their design and capability requirements for their virtual laboratory blueprint. Furthermore, a framework use case is demonstrated by not only surveying five types of VR devices ranging from low-immersive to full-immersive along with their capabilities (i.e., hardware specifications, cost, and availability) but also considering the interaction techniques in each VR device based on the desired laboratory task. To validate the framework, a research study is carried out to compare these five VR devices and investigate which device can provide an overall best-fit for a 3D virtual laboratory content that we implemented based on the interaction level, usability and performance effectiveness.

To my parents, in memory of my grandparents.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

With the recent development and maturation of Virtual Reality (VR) technology over the past decade, an increasing number of consumer-based VR hardware and devices are gradually integrating into our daily life, rapidly changing the ways humans interact with various devices and technologies. Today, VR not only plays a significant role on the stage of entertainment and gaming industry but also shines its spotlight across different realms with serious purposes including healthcare, business, art, and military, as well as training and education [1, 2] [1].

Particularly in engineering laboratory education, hands-on activities are essential exercises for students to understand related engineering formulas and concepts. With the help of VR technology, a realistic 3D laboratory environment can be simulated in an interactive and engaging way for students to practice virtually before their experiment sessions take place on the physical laboratory equipment. This type of VR setup may potentially offer many educational benefits. Firstly, making mistakes in a simulated environment is completely safe, which allows students to learn from their mistakes without being concerned about any potential risks or hazards caused by improper use of the laboratory equipment. Secondly, a virtual laboratory offers flexible accessibility in terms of timing and location. Students can practice the experiment virtually anywhere and anytime. This is especially helpful for distance learning students who often may not have equivalent resources compared to on-campus students. Thirdly, using virtual laboratories may drastically reduce the equipment maintenance cost. Students can practice virtual experiments

[1] IEEE Transactions and Journals style is used in this thesis for formatting figures, tables, and references.

frequently without worrying about any wear and tear on the lab equipment, and therefore, the equipment life-cycle may extend for a much longer period.

Given these potential benefits of using virtual laboratories for engineering laboratory education together with a variety of VR devices and hardware to choose as a learning platform for virtual laboratories, a question naturally arises especially from a developer and researcher standpoint: which VR device, among the well-known ones on the market today, can best suit the overall design requirement (hardware, software, related tasks as well as interaction) of a 3D interactive virtual laboratory?

1.1 Problem Statement

Although a vast amount of literature has demonstrated that students' learning and engagement can be improved when using virtual laboratories tied with their corresponding VR devices [3-8], however, to our best knowledge, very few have *(i)* provided detailed reasons for choosing the proposed VR device as the learning platform for their virtual laboratories and *(ii)* laid out what specific factors that could affect students' performance while using the VR system. One study from Kronqvist *et al.* compared three VR devices: a headband, 3D glasses and a head-mounted display (HMD) to investigate and measure the virtual environment (VE) authenticity including factors such as the level of immersion, the feeling of control and system usability. These three devices were used to do simple tasks in a 3D virtual car model [9]. Although the study provides useful insights of evaluating and measuring VE authenticity in the context of human-technology interactions, the VR devices they used for evaluation only contained headwear VR devices, other mainstream VR platforms were not covered in this study. Amirkhani and Nahvi developed an interactive 3D virtual physics laboratory using a haptic device as the main source of input [4], and its research primarily focused on students' learning and performance aspects compared to the study of Kronqvist *et al.* where the human-technology interaction aspect was heavily emphasized.

With the rise of popularity in VR as an emerging technology in recent years, a new wave of VR devices and hardware are becoming affordable consumer products. According to the statistic from the 2017 International Consumer Electronics Show (CES), there were a total of 71 VR related exhibitors at the show, which almost doubled the amount from the previous year [10]. As a variety of VR devices continue to offer new exciting features, how does one choose a specific VR device among the ones on the market that can best fit and satisfy the design requirements for developing an educational 3D interactive virtual laboratory? To answer this question, a constructive utility framework is needed to help decision makers efficiently choose a type of VR device to match with the design requirements of their 3D interactive virtual laboratory blueprint. In addition, this framework not only surveys a few different types of VR devices and their capabilities (hardware and software specifications) but also takes the interaction techniques based on a set of generic laboratory tasks into account.

1.2 Purpose

The main purpose of this study is to conduct both quantitative and qualitative research to observe participants' performance in a 3D interactive virtual laboratory, as well as investigate a few key factors such as the effectiveness of the immersion level, control factors (interactivity), system usability, concentration, etc. in VR that may potentially affect and contribute to students' performance in virtual laboratory settings. To fulfill this purpose, the study will focus on those original aspects: *(i)* design and implement an interactive and immersive 3D virtual laboratory for an experiment – the Jet Impact Force on Vanes (Jet-force Experiment) in the junior level course (ME 305) at Old Dominion University on five distinctive VR platforms ranging from a fully portable device such as a mobile device to a large scale virtual environment such as the CAVE, *(ii)* provide a utility framework that can assist decision-makers choosing the suited VR device matching with the design requirements along with its interaction techniques based on specific laboratory tasks, *(iii)* test and run the framework with a use case, *(iv)* conduct a research study containing both the quantitative and qualitative assessment targeting participants' general performance along with the observation of those key factors aforementioned as a method to further validate the proposed utility framework, and lastly *(v)* analyze the quantitative and qualitative results and provide a detailed analysis to compare those key factors that may contribute to a potential increase in learning performance benefitting from different VR platforms.

1.3 Research Questions

The key research questions are: *(i)* Can a utility framework provide general guidance for decision-makers/developers to pick a suitable VR platform for 3D interactive virtual laboratories (in engineering and science subjects)? *(ii)* What type of VR platform is the most suited for a learning and interaction experience particularly for a hands-on intensive engineering laboratory experiment (such as the Jet-force experiment)?

1.4 Anticipated Contribution

The anticipated contribution of this research reveals three unique aspects: (*i*) formulating a utility framework that is specifically tailored to the design and implementation of 3D interactive virtual laboratories in engineering and science education, (*ii*) designing and implementing the 3D interactive Jet-force experiment across five VR environments ranging from low-immersive to full-immersive devices (mobile, desktop PC, Z-Space tablet, VR headset, and CAVE), and (*iii*) contributing to a basic understanding of how different factors (immersion, interaction, usability, emotion, etc.) vary from different types of VR devices or systems applied to engineering laboratory settings.

1.4.1 Formulating a Utility Framework

A three-in-one (task-based, interaction-oriented, and device property-focused) utility framework will be formulated to help users efficiently decide on an adequate VR device as the platform to run for their designed virtual laboratories in engineering and science settings. This utility framework may potentially assist decision-makers including institutions, PIs, and developers to integrate VR technologies in engineering and science education, particularly in hands-on intensive laboratory courses. In addition, the proposed utility framework may provide decision makers insights on forming a perfect match between an ideal VR device and the design requirements of a virtual laboratory. Decision makers also have the flexibility to weigh their options to see the "what-if" scenario based on each capability of a VR device in terms of its software and hardware specifications, tasks functionalities, and interaction techniques.

1.4.2 Design and Implementation of a Multi-platform 3D Interactive Virtual Laboratory

This research work aims to design and implement the Jet-force experiment across five representative VR systems (mobile, desktop PC, Z-Space tablet, VR headset, and CAVE) ranging from low-immersive to full-immersive devices. This process includes migrating previous work from the outdated game engine 3DVIA Virtools to a new game engine Unity. All the game logic design and user interface will be reworked and started from scratch in Unity.

1.4.3 A Comparative Study on Assessing VR Capabilities

This dissertation will contribute to a basic understanding of how various factors (e.g., level of immersion, control, concentration, usability, etc.) vary from different types of VR devices when completing virtual laboratory experiments, as most of the current literature has not investigated this topic in a holistic approach. A research study containing both the quantitative and qualitative assessment targeting on participants' general performance on all five VR devices will be carried out to further address this topic as well as to validate the utility framework.

1.5 Organization

Chapter 2 reviews related background information and concept of VR along with its applications in engineering and science education. Chapter 3 reviews and discusses recent published articles and literature on the learning effectiveness on various VR platforms as well as a comparative study of interaction techniques. Chapter 4 presents the methodology of developing the three-dimensional (3D) virtual laboratory on five distinctive VR platforms, constructing the utility framework, in which a use case is tested and run through as well as the describing the research design for quantitative and qualitative evaluation. Chapter 5 analyzes the quantitative and qualitative results and provides a detailed investigation to compare key factors in VR platforms that may contribute to a potential increase in learning performance benefitting from different VR hardware and devices. Chapter 6 concludes the dissertation by discussing the limitation, drawbacks, and future work of this study.

CHAPTER 2

BACKGROUND

This section provides the background information of VR in general along with the explanations of some VR terminologies. In addition, recent research work related to this proposal will be discussed.

2.1 Human-Computer Interaction

Human-Computer Interactions (HCI) refers to a multidisciplinary field of studying the interactions between human and computer systems, with its emphasis on the practice of usability [11]. Research in HCI became in-demand with the expansion of personal computers (PCs) in the 1970s, where the first modern 3-button mouse was available for personal use as the primary input device for PCs, along with the distribution of the very first PC namely the Xerox Alto [12]. Today, with the rapid growth in computer and VR technology, sending instructions and commands to computers or other electronic devices is not only limited to the traditional mouse-keyboard interaction paradigm. The way people interact with computers and other electronic devices has shifted dramatically to a new level. Cellular-phones are no longer just number pad presses; multi-touch technology has been the dominating interaction technique in smartphones today since the release of the first generation of Apple iPhone in 2007 [13]. With the introduction of the Microsoft Kinect, gesture-based interaction and motion tracking set a milestone for the natural user interface (NUI). Using hand gestures and body motion in substitution of gaming controllers are gradually becoming a mainstream interaction modality for current gaming consoles and VR devices.

As the term HCI implies, it is relevant in both research areas of human and computer. From the human aspect, cognitive psychology, human behavior studies, human factors, and ergonomics are research subjects that investigate how humans can use various senses to interact and communicate with computers efficiently [14]. On the other hand, techniques in computer graphics, development environment, and user interface are research areas on the computer aspect that explore how computers and other technology can be efficiently improved regarding the usability [15]. Hewett *et al*. proposed the idea that HCI is not only just about human and computer but also related to the problems of fitting computers and the context of their uses as well as the process of building and measuring interaction design [15]. These ideas were organized and categorized into five interrelated aspects: "(N) the nature of the human-computer interaction, (U) the use and context of computers, (H) human characteristics, (C) computer system and interface architecture, and (D) the development process" [15]. Fig. 1 illustrated these topics in a diagram form. The objective of this diagram, according to Hewett *et al*., is to "provide a taxonomy that maps the HCI research areas that is worth knowing" and to "specify the connections with other fields." However, Hewett *et al*. also suggested that "such a list cannot hope to be complete or even non-controversial, but it should be heuristically useful in the practical business of preparing courses in HCI" [15]. This is relatively true because while the fundamentals of the HCI topics remain the same, as technology progresses, it is essential to not only emphasize the usability aspects in HCI but also consider integration with the newest technology and interaction techniques to ensure that the research area of HCI stays current and updated.

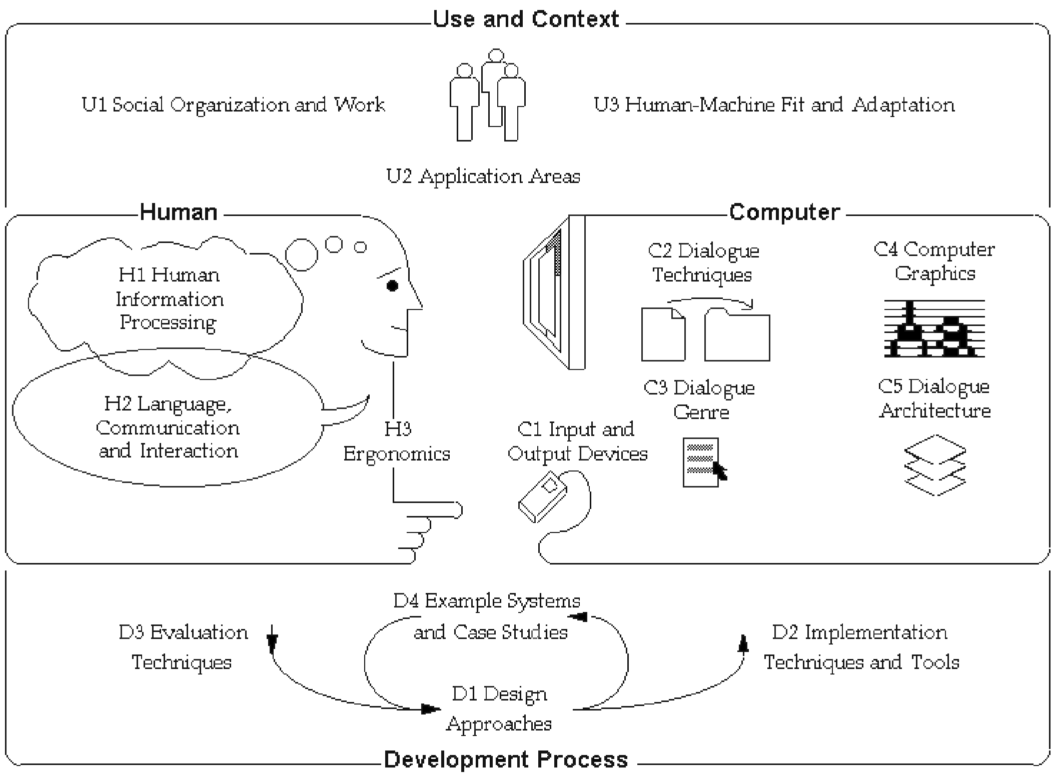


Fig. 1. Human-Computer Interaction Topics from Hewett *et al*. (1992) [15]

2.2 User Interface

A user interface is a “bridge” linking the interactions between human and computers/machines. It refers to how data and commands are entered by users and how information is received and displayed on the screen [16]. Fig. 2 shows a human-computer interface loop. A user can send commands and interact with a software system on a computer using an input device through the user interface software; the information then is reflected at the user to take further actions through the user interface software and an output device. A graphical user interface (GUI) is a user interface containing visual icons, menus, indicators, and pointers that enable the interaction and communication between human and electronic devices. For example, almost all modern operating systems (e.g., Windows, Linux, and MacOS) today allow users to send commands and instructions by clicking on graphical objects (e.g., desktop icons and menu options). Before GUI became widespread as the leading user interfaces in operating systems, a text-based or command-line user interface was the primary type of user interface from the late 1970s to early 1980s [17]. A well-known example of a command-line user interface is the MS-DOS, an operating system that allows users to send instructions to the computer by entering text-based commands. To accommodate the natural human gesture, NUI brings a fresh concept of interacting with computers/machines using hand gesture or other body motion. NUI refers to the interaction between human and computer through intuitive actions related to natural human behavior [18]. Examples of NUI include 2D touchscreen interfaces (e.g., the touchscreen of a smartphone) and gesture recognition systems (e.g., Microsoft Kinect and Leap Motion). Another commonly seen type of user interface is the audio-based user interface, which has been widely adopted in modern smartphones and other smart home devices. Users can give commands to the device by directly speaking to it. This interface offers users a convenient and fast way to give commands and access the information, especially when their hands are occupied with other tasks.

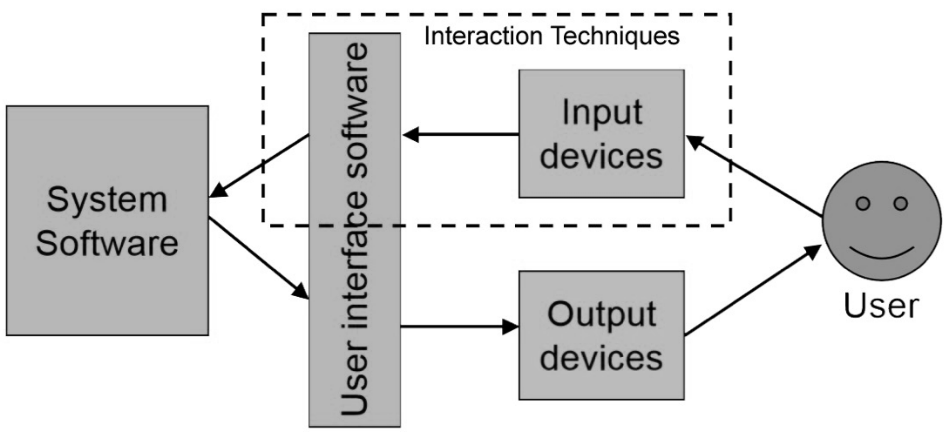


Fig. 2. Human-Computer Interface Loop from Bowman (2006) [19].

2.3 Usability

Usability, by definition, is the ease-of-use and learnability of a human-made object [20]. In the users-centered design paradigm, it is often vital to emphasize maximizing usability to ensure the designed system meets its intended goals. ISO 9241-11 provides a usability framework that illustrates how usability can be measured and evaluated based on three fundamental principles: effectiveness, efficiency, and satisfaction [21]. The effectiveness shows how accurately users can complete given tasks or achieve specific goals in a designed system or product while the efficiency focuses on the how these tasks can be done using the least amount of time and resources. Satisfaction implies how pleasant it is to use the designed system from the user perspective. The framework from ISO 9241-11 also demonstrates that usability of a product is not only determined or measured by key principles, but also depended on the actual context of use – including components such as the user information (users' education background, skills, experience and physical attributes, etc.) the tasks that achieve given goals, the equipment (both hardware and software characteristics) as well as the environment (physical and social environment). Fig. 3 illustrates the usability framework from ISO 9241-11.

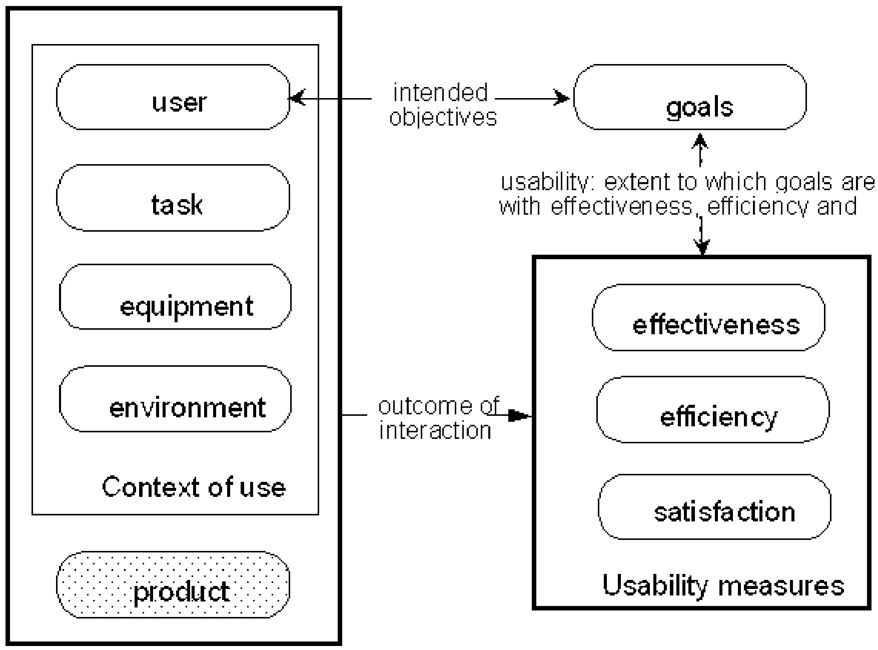


Fig. 3. Usability Framework from ISO 9241-11 [21].

2.4 Virtual Reality

Virtual reality (VR) is an artificial world that replicates the real-world environment generated by computers and simulates the physical presence of a user in a virtual environment [22]. Unlike conventional user interfaces, participants experiencing VR are immersed in the virtual environment and can interact and communicate with the virtual objects and avatar representations by using different types of input devices such as a joystick, a gamepad, or a haptic controller as well as an audio-based input device such as a microphone. Although most VR systems bring users stunning visual and audio experiences, information can also be transferred to users through other senses such as touch and even smell. Compare with VR, augmented reality (AR) works similarly. However, AR simulates virtual interfaces and objects on top of the real-world environment while all the components generated and displayed in VR are entirely virtual. AR is often confused with augmented virtuality (AV), although they both blend virtual and real-world elements. The difference is that AV is a virtual world with a bit of reality in it while AR is a reality with a bit of virtual in it. For example, a meteorologist standing in front of a green screen with a dynamic virtual weather background mapped to it is considered as AV. On the other hand, a pair of Google Glasses displaying information virtually on top of the real world is an example of AR. Milgram *et al.* proposed a scale called the virtuality continuum as illustrated in Fig. 4 [23]. This scale ranges from a real environment to a completely virtual environment. Everything in between, including AR and AV, is considered a mixed reality (MR).

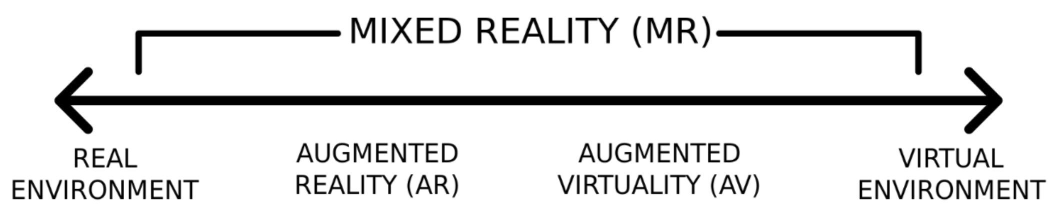


Fig. 4. Virtuality Continuum Scale Milgram *et al.* (1994) [23].

2.4.1 Types of VR

A VR environment sometimes can be categorized based on the immersion level: low-immersive, semi-immersive, and immersive (full-immersive) [24]. When being presented in a virtual environment, if users are experiencing less awareness of the actual surroundings, it implies that more immersion level is being produced from the virtual environment, and vice versa. An example of a low-immersive VR system includes a typical desktop PC setup. This type of VR system is typically paired with conventional input devices such as a keyboard, a mouse, or a joystick for basic interaction purposes. Compare with low-immersive VR systems, Semi-immersive VR systems have moderately higher immersion and interactivity level. Examples of semi-immersive VR systems include a desktop PC with 3D stereoscopic monitors, a 3D TV or a 3D holographic tablet. They allow users to view information from stereoscopic displays with a pair of 3D glasses. Some semi-immersive VR systems are paired with input devices with a higher level of interactivity. An example would be a haptic input device that provides touch feedbacks and six degrees of freedom. An immersive VR system delivers users the strongest immersive experience by not only isolating their senses from the real world but also feeding them with virtual information. A typical example of immersive VR systems includes a VR HMD, which is a VR wearable headset with featured head position tracking, OLED displays, and surrounding audio. Such headsets, including the Oculus Rift and the HTC Vive, provide a fully immersive VR experience in a portable form factor. Another type of immersive VR system is the CAVE, which is usually a cube-shaped room-sized VR facility with multiple projection screens as the walls. A CAVE is a large-scale virtual environment that can have various participants interacting and accessing virtual information collaboratively. TABLE 1 illustrates the modified comparisons of a few factors such as resolution, sense of immersion, interaction and price among the three types of VR systems that are based on the level of immersion.

TABLE 1

COMPARISONS AMONG THE THREE TYPES OF VR SYSTEMS BASED ON IMMERSION LEVEL FROM ALQAHTANI *ET AL*. (2017) [24].

	Low-immersive	**Semi-immersive**	**Immersive**
Resolution	Low to medium	Medium to high	High
Sense of Immersion	None to low	Medium to high	High
Interaction	Low	Medium	High
Price	Low cost	Average cost	Expensive

2.4.2 VR System Taxonomy

To better illustrate the classification of VR systems intuitively, Muhanna proposed a VR system taxonomy not only based on the level of mental immersion but also incorporated with examples of VR technology and hardware [25]. This idea is very similar to the classification techniques from Alqahtani *et al*. [24]. As demonstrated in Fig. 5, VR systems can be categorized into two main types: basic and enhanced. Basic VR systems have the lowest immersion level, and they include a hand-held mobile device such as smartphones and tablets, as well as monitor-based VR systems such as a traditional desktop PC setup. The enhanced VR systems are divided into partially immersive (semi-immersive) and fully immersive. Partially immersive VR systems include systems with a large projection screen (including some that have the capability of display images in 3D stereoscopic) such as wall projectors and an ImmersaDesk. Lastly, fully immersive VR systems, such as the CAVE and an HMD, typically can display virtual environments with a large field of view, making participants less aware of their physical surroundings.

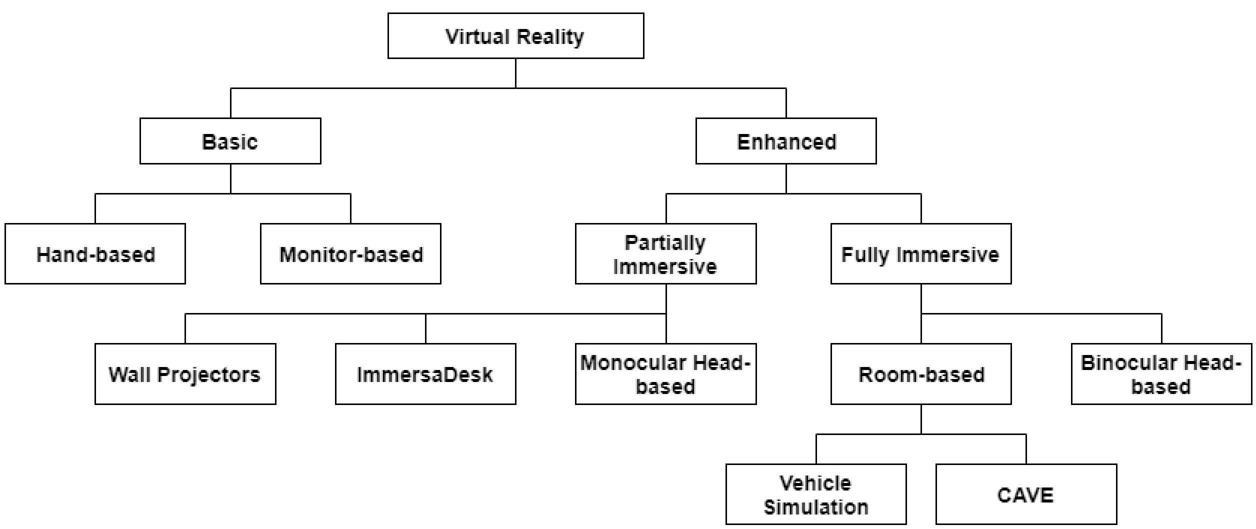


Fig. 5. Taxonomy of Virtual Reality Systems based on Level of Immersion and Associated VR Technology [25].

2.4.3 VR Devices/Hardware

A VR device is a piece of hardware equipped with the capability of running a virtual environment and then output the visual information to either a built-in or external display. Some VR devices are standalone systems (e.g., mobile devices such as a smartphone and tablet) that do not require external hardware such as a PC or a monitor to run and display the virtual environment. However, most of the VR devices (e.g., VR headsets such as Oculus Rift and HTC Vive) rely on external hardware such as VR-Ready[2] desktops or laptops to run those 3D virtual environments that are relatively graphic demanding.

Mobile VR

A mobile VR system provides VR experiences in a compact form factor. Smartphones (e.g., Android phones, iPhones, and Windows Mobile phones) and tablets (e.g., Android tablets and iPads) are examples of mobile VR systems. They are portable in size and cost-effective compared with other VR devices. Most current mobile devices, including smartphones and tablets, have screen sizes in diagonal ranging from 4.5 to 12 inches with weights ranging from a few ounces to 3 pounds. Concerning the cost, the lower-end to mid-range mobile devices (regarding the device specifications) have market prices ranging from $50 to $400, which is much more acceptable for average consumers than other VR devices that cost more than $500. In addition, mobile VR systems are standalone, meaning they can run on their own without the need of a computer. Regarding accessibility and ownership, smartphones are more frequently used than other VR devices. According to a survey study done by Rainie and Perrin from the Pew Research Center, in 2016, more than three quarters (77%) of adults in the United States owned a smartphone [26]. To

[2] VR-Ready is a term to describe a PC (specifically the graphic card component) that meets the performance requirements to deliver an optimal VR experience.

enhance the immersive experience for mobile devices, Samsung VR gear and Google Cardboard are VR headsets made explicitly for smartphone users. These headsets allow users to insert the smartphone into a designated slot and view the virtual scenes displayed on the smartphone screen through the headset lenses. While smartphone VR headsets offer an immersive VR experience, touchscreen interactions are temporarily unusable since a smartphone is being used as part of the headset. Only a limited number of VR applications that are specifically designed for those VR headsets allow user interaction by pairing a Bluetooth controller with the smartphone. Although smartphone VR headsets provide a higher immersion level, it takes away the advantage of using the built-in touchscreen for interaction purposes. Having an extra input device such as a Bluetooth controller or a stylus in hand, for most people, is not always a convenient choice.

Desktop VR

A desktop VR system is typically powered by a desktop computer containing either an integrated or dedicated GPU[3]. The basic setup of a desktop computer includes a computer tower (containing hardware components such as CPU, GPU, ram, hard drive, motherboard, and graphics card), a monitor (display visual information), a pair of speakers (output audio) and peripherals such as a keyboard, a mouse or a joystick (provide interaction). Although a desktop VR does not offer much portability, its hardware components can be easily upgraded down the line. The cost of mid-range computers is usually between $400 and $700, which is almost $200 to $300 cheaper in comparison with a portable laptop that has similar hardware specifications. In addition, the accessibility of desktop computers is generally universal as they can be accessed from schools,

[3] Integrated GPUs (e.g. Intel HD Graphics integrated in the Intel processor) and Dedicated GPUs (e.g. NVIDIA GTX 970) that meet the requirements of running 3D VR applications. A technology where a desktop computer equipped with multiple dedicated GPUs is called Scalable Link Interface (SLI). Such technology is capable of parallel computing and increasing processing power in terms of 3D computer graphics.

public libraries, and homes. To improve the immersive experience, a 3D stereoscopic monitor can be added as the primary source of display. Interaction with a desktop computer usually takes place with the use of a keyboard and a mouse. Other input devices such as a gamepad or a joystick can also be paired with a desktop computer, depending on the input requirement of the VR application itself.

VR Headset

A VR headset is an HMD that features stereoscopic lenses as the primary display and motion tracking (e.g., using accelerometer or gyroscope) for tracking head or eye movement [27]. Although a VR headset seems to provide the most immersive experience among any other VR devices by shutting down users' senses from the outside world, almost every VR headset requires some external hardware to work (e.g., Oculus Rift VR headset requires a PC connection). This, to some extent, limits its portability unless a user decides to use a more portable VR-Ready laptop over a desktop PC.

Currently, the two most popular PC-based VR headsets as consumer products are the Oculus Rift and the HTC Vive [28]. The Oculus Rift is a VR headset developed by a group called Oculus VR, which was later acquired by Facebook. The headset provides an OLED display for each eye with full HD 1080x1200 resolution and 110 degrees field of view. The headset can be powered through a USB 2.0 or 3.0 port on a PC. Visual information can be presented on the headset display via an HDMI cable that connects between the headset and a PC. The headset also comes with a wand-like Oculus Touch controller as the input device. Alternatively, users are also able to use other input devices such as a conventional gamepad or a gesture-based motion controller called Leap Motion. The HTC Vive is another newly released VR headset that is developed by HTC.

Compared with the Oculus Rift, the HTC Vive is relatively similar regarding hardware specification and interaction techniques (e.g., similar display technology and input controller). However, the noticeable difference is the tracking system. The tracking system in the Vive includes two base tracking stations that deliver 360 degrees of motion tracking. Thus, the Vive seems to offer more flexibility in terms of room-scaling ability as the tracking allows the user to stand and walk as opposed to Oculus Rift's seated headset. Concerning the cost, the Oculus Rift is priced at $400 while the Vive is priced at $600. However, as mentioned previously, these PC-based VR headsets require either a desktop or a laptop with a VR-Ready graphics card, which also may contribute to additional cost overall. In terms of accessibility, VR headsets are consumer products that can be easily purchased online or in-store, although there are only 5% of internet users who owned a VR headset/device based on a statistical study done by Buckle from the Global Web Index [29].

3D Stereoscopic Tablet

A stereoscopic tablet is a type of display that generates a holographic-like virtual three-dimensional object realistically [30]. Stereoscopy tricks our brain by providing a prospective pair of slightly separate images for both eyes (one for left, one for right) as a stereo pair for our brain to rebuild a 3D image [31]. The zSpace.Inc and Hewlett-Packett are the leading companies that produce 3D stereoscopic tablets such as the Z-Space 200 model and the HP zVR 3D display. Both tablets work comparably regarding hardware specification and interaction techniques. They feature a stereoscopic display with sensors and infrared light on the top bezel to perform tracking for both a pair of passive polarized eyewear and a haptic-based input stylus. These tablets allow users to interact with virtual objects in stereoscopic 3D in a volume in front of the display using an input stylus, which is a laser pointer-like pointing device equipped with three physical buttons and 6 degrees of freedom (DOF) capability. Grabbing 3D objects using buttons on the stylus seems intuitive and provides a similar experience of grabbing real objects with thumbs and fingers. Regarding the cost, the price range for these tablets is between $4000 and $5000. Also, these tablets need workstation computers with specific professional graphics cards (e.g., NVIDIA Quadro Series or AMD FirePro Series), which may bring up the overall cost to a $6000 mark. Some newer models of Z-Space are all-in-one systems and have advantages of running applications without using external computers, although the unit price tends to be roughly $2000 higher than the $6000 mark. Regarding the accessibility, the Z-Space tablet has been installed and used by 150,000 students in schools and universities nationwide and other parts of the world [32].

CAVE

A CAVE is a large-scale virtual environment in a cube-shaped room with projection screens as the walls and floors of the room. As users walk into the CAVE, they are immediately immersed in the environment and being surrounded by virtual images displayed on the projection walls and floors. This is especially helpful regarding 3D visualizations, as Limniou *et al*. have demonstrated that using CAVE can help chemistry students visualize and interact with 3D molecules better than using the conventional 2D display [5]. A typical CAVE setup includes the following hardware components: projection screens, DLP-link ready 3D projectors for each screen (at least 120 Hz to support active stereo through quad buffer), a computer containing a professional graphics card supporting quad buffered stereo, input device (e.g. a gamepad, a Wii remote or a Kinect sensor, etc.), active shutter 3D glasses as well as an optional tracking system to track users' movement in the virtual environment. Compare among other VR devices; a CAVE setup is the most expensive VR environment. An entire commercial CAVE setup can be priced at a range between $10,000 to $30,000, depending on the types of hardware and their specification. Although the accessibility of a CAVE can be relatively difficult as many schools and universities do not adopt it, its large space has the advantage of hosting multiple participants collaborating in a virtual environment over any other VR devices.

VR Device Comparisons

TABLE 2 describes the comparisons of the VR devices mentioned in the previous sections containing three factors: accessibility, portability, and cost. The accessibility factor is based on how easy it is to purchase the device as an average consumer. For example, a mobile device can be easily purchased either online or from any electronics department stores while a CAVE is a commercialized product that needs a more complicated ordering process. The portability factor is based on the size of the device. For instance, mobile devices that can be carried in a pocket without the need for any other transportation is considered as "portable." The cost factor is based on the current average market price of each VR device as well as other required hardware components for that VR device. The approximate value ranges are reflected in TABLE 2.

TABLE 2

COMPARISONS OF VR SYSTEMS BASED ON ACCESSIBILITY, PORTABILITY, AND COST

	Accessibility	**Portability**	**Cost**
Mobile VR	Consumer electronics	Portable	Low
Desktop VR	Consumer electronics	Semi-portable	Low
VR Headset	Consumer electronics	Portable	Medium
3D Stereo Tablet	Consumer electronics – requires bulk purchase	Semi-portable	High
CAVE	Commercialized products	None-portable	High

2.4.4 Input Devices

An input device is a peripheral that allows users to send information or data to a VR system while an output device is a piece of hardware that delivers the information out of the system to users. Both devices are essential components of a VR system, as they provide interaction and communication between the user and the system. According to Ramirez's research, input devices can be classified into two categories: desktop (standard) and immersive input devices [33].

Desktop (Standard) Input Devices

Desktop (standard) input devices are commonly used in our everyday life such as mice, keyboards, joysticks, gamepads, and touchscreens.

- Mice: A computer mouse, can be connected either in wire or wireless, is a 2D pointing device that resembles the shape of an animal mouse. Most of the standard mice have two physical buttons (left and right) and a scroll wheel in between the buttons. The scroll wheel also can be used as a physical button. As an input device, although a 2D mouse can provide accurate pointing and selecting reactions in low-immersive 2D and certain 3D environment, they may not be a good fit for advanced interaction in a more immersive 3D environment.

- Keyboards: A computer keyboard is typewriter-style hardware consisting of various physical keys labeled with English alphabetical letters, numbers, symbols and other commands for typing words and sending an instruction to a computer or other compatible systems. In desktop VR applications, different interaction and functionality can be mapped on corresponding keys on the keyboard.
- Joystick: A joystick is a type of input device that allows users to control various virtual machines using one hand. A typical joystick consists of a hand-sized stick with a few physical buttons pivoting on a base. Since a joystick resembles the appearance and functionality of the control device in the aircraft cockpit, it is commonly seen being used for operating virtual flight and crane simulator.
- Gamepad: A gamepad, also known as a gaming controller, is a type of input device mainly made for video game consoles or computer gaming that can be held by two hands. A standard gamepad consists of a set of physical buttons and a four-way directional pad or an analog stick for the right and left thumb respectively. In 3D games, a directional pad has limitations regarding the character's 2D movement as it only allows the character to move in four directions (forward, backward, left and right). Using an analog stick can solve this issue by allowing the character's 2D movement in every possible direction. Most modern gamepads now include shoulder buttons (e.g., left and right triggers or bumpers) in addition to standard buttons. Some gamepads also have a built-in vibrator for haptic feedback.
- Touchscreen: A touchscreen, serving as both an input and an output device, is a type of electronic display that can detect the location of a touch from the user. Most touchscreens

are also equipped with multi-touch technology that can sense not only multiple gestures (e.g., tap, press, pinch, rotate, etc.) but also touch pressures. Most modern portable electronics, such as smartphones and tablets, have a built-in touchscreen with multi-touch capabilities.

Immersive Input Devices

Immersive input devices usually provide users with more advanced interactions and immersive experiences in virtual environments than standard input devices. Examples of immersive input devices include motion tracking input devices and styluses/wands.

- *Motion tracking input device*: A motion tracking input device can capture users' body movement in real time and send this information to the computer, which then interprets the tracking information and reflects the position and orientation of the movement in the virtual environment to users.
    - *Leap Motion*: Leap Motion controller is a small USB-powered hand gesture tracking input device that can be connected to a PC. It can be placed on a flat surface, facing upward or it can be attached on the front surface of a VR headset. Equipped with two cameras and three infrared LEDs, the device can track all ten fingers on both hands, with a hemispherical interaction area of roughly two feet in radius [34]. With the Leap Motion controller, users can manipulate virtual objects in a more immersive and realistic way with their bare hands. Making gestures such as pinch, finger swipe, wave, and grab is a natural interaction that cannot be done with standard input devices.

- *Oculus Touch/HTC Vive Controller*: Both devices are input devices for their respective VR headsets: Oculus Rift and HTC Vive. Oculus Touch also called “Half Moon” is a pair of tracked controllers that deliver users a “hand presence.” Each controller features a half moon shape with two physical buttons, an analog thumbstick, a trigger button as well as infrared LEDs for tracking purposes [35]. In addition to the hand tracking feature, Oculus Touch also offers haptic feedback. Similarly, HTC Vive controller is a pair of tracked input device designed for the HTC Vive VR headset. It is a stick-shaped controller that can be easily held in hand with a ring shape pointed up on the top. The controller features two physical buttons, a trigger button, a circular touchpad and a total of 24 infrared sensors embedded inside of the ring [36]. Both input devices work similarly in terms of immersive interaction and tracking. However, Oculus Touch controllers allow hand gestures to be represented virtually in VR environments.
- *Microsoft Kinect*: A Kinect is a motion tracking input device developed by Microsoft. It features a depth RGB camera and an infrared emitter with a monochrome CMOS sensor. These two components work together by projecting light patterns and receiving that information to produce a depth image of the physical environment, which then is analyzed and calculated to distinguish human body parts, joints, and movements. The available range for the Kinect is roughly 3 meters (approximately 10 feet) from the sensor, anything beyond that range will result in losing accuracy of the depth map [37]. Although the Leap Motion has a shorter range of interaction area, it provides much higher precision than the Kinect [38]. This means that the Leap Motion controller is designed to track a smaller

portion of the body such has precise hand gesture-based control while the Kinect is ideal for tracking the entire body movement.

- *Stylus/wand*: A stylus or a wand, is a type of direct pointing input device equipped with optical sensor technology that allows user interaction by directly pointing at the display. This indicates that the pointer on the display screen is at the same physical location as the pointing input device. Compared with the direct pointing input device, although the indirect pointing input device is not at the same physical location as the on-screen pointer, it can, however, translate its 2D movement on the display screen.
    - Stylus: A modern stylus is a pen-shaped like input device that is commonly paired with touchscreen devices such as a smartphone or a tablet. It functions as a finger input but with more accuracy and precision for selecting, writing or drawing purposes. There are two types of stylus: passive and active. The passive stylus works identically like a finger input with no electronic components. Thus, no electronic communication is done between the stylus and the touchscreen. On the other hand, an active stylus uses electronics to communicate with the touchscreen. It provides users with a real pen-like experience by enabling features such as pressure sensitivity so that writing and drawing appear to be more natural.
    - *Wand*: A wand-like controller is a direct pointing input device that can be held in one hand. It consists of a set of physical buttons for performing various tasks such as menu selection and 3D object manipulation. Some wand controllers also feature position and motion tracking capability. One example is Nintendo's Wiimote, which is the main controller designed for the Wii gaming console. The Wiimote controller can also be connected to a PC wirelessly via a Bluetooth connection. The

controller features optical sensor technology (IR camera) for detecting IR lights. It is usually paired with a sensor bar containing 2 IR lights that can be placed near the display for tracking where the controller is pointing on the display screen. The Wiimote also features an accelerometer for capturing motion with 6 degrees of freedom (DoF) [39]. Another similar example of a wand-like controller is the Oculus Touch/HTC Vive as mentioned in earlier sections.

- *Hybrid of Stylus/Wand*: One example of a hybrid of stylus and wand is the Z-stylus, which is the primary input device for the Z-Space tablet. The stylus consists of three physical buttons that perform different tasks depending on the virtual environment and an IR LED for 6 DoF positional tracking. Different from a traditional stylus that often needs physical contact with the display screen for interaction, the Z-stylus can generate a virtual light ray in the virtual scene that follows the position of the hand so that interaction can take place without any physical contact with the screen. With 6 DoF tracking, users can pick up the virtual objects and rotate their wrist to observe the objects naturally.

2.4.5 Display Devices

A display device is a type of output device that can present the information visually on a digital screen. Based on literature from Mendes *et al*., there are three main types of display that are generally used for virtual environment systems: screen constrained, stereoscopic window, reality replacement [40].

- Screen constrained display: Screen constrained displays are the least immersive output devices. Examples are those of traditional desktop monitors or TV screens, which are typically 2D screens with no stereoscopic capability.
- Stereoscopic window: Stereoscopic window output devices are semi-immersive displays that have stereoscopic depth cues. These devices are more immersive than screen constrained displays but less immersive than reality replacement devices. A 3D TV, a 3D desktop gaming monitor, or a Z-space tablet display are examples of stereoscopic window output devices.
- Reality replacement: Reality replacement are fully immersive output devices with stereo depth cues which can replace users' reality with complete virtual information. An HMD and a surround-screen display CAVE system are examples of reality replacement displays.

2.4.6 VR Application Areas

As VR technology continues to advance, there has been a wide range of applications being developed in various domains including, but not limited to, sports, healthcare, military training as well as education.

Sports Training

In sports training, Li developed a real-time interactive VR environment for two-player table tennis simulation [41]. The objective of Li's research was to create a realistic simulation tool for training both single and duo table tennis players. Miles *et al*. presented their work on designing a CAVE-like immersive virtual environment for training rugby players [42]. The goal of this research is not only to train players' ball passing skills but also to examine whether the use of stereoscopic display would affect participants' ability to perceive distance accurately.

Medical and Health Care

In the health-care and medical domain, VR simulations are especially helpful for training medics because there are no potential risks of injuring the actual patient, as the training process can be done entirely on virtual simulators. Seevinck *et al*. described the development of a haptic-based surgical wound debridement device to train nurses to perform a simple procedure of cleaning the debris from a wound that was caused by a motorcycle accident [43]. Using a force-feedback haptic device adds a sense of touch for a higher level of training realism for practicing the removal of the debris from the wound. Scerbo *et al*. showed their work in a virtual operating room (VOR) in a CAVE-based environment for training surgical procedures [44]. The VOR is also capable of supporting trainees to interact with a surgical team comprised of real and virtual team members with speech recognition.

Military Training

In the military simulation domain, VR simulators play significant roles for training certain injury-prone or risky scenarios such as parachute landing or flight training. Parasim, made by Systems Technology Inc., is an interactive realistic hybrid parachute simulator that can be used to help jumpers master the techniques of parachute maneuvering [45]. The Microsoft Flight Simulator is one of the most comprehensive flight simulator software programs that can be run on a PC [46]. This simulator can also be paired with a Saitek Pro flight simulator cockpit shell for a more realistic training experience [47]. Bhagat *et al*. presented their work on a cost-effective interactive 3D virtual shooting simulator for military live firing training [48]. To enhance the realism of the firing training, Bhagat *et al*. adopted a hybrid system consisting of a 1:1 real-scale rifle gun with recoil feedback and an invisible laser infrared paired with an immersive screen that delivered interactive training modules. The study demonstrated better training outcomes than conventional live firing training. In addition, this hybrid simulation system provided a cost-effective solution so that training firing skills can also be fun and interactive without even firing a real bullet.

Education

Education is another domain that adopts VR technology for teaching and learning. Limniou *et al*. developed a fully immersive environment in the CAVE for chemistry education [5]. This learning system allowed students to visualize and observe molecules in a dynamic way. Study results showed that students had a significantly better comprehension on molecules' structure and chemical reaction when participating the CAVE setting (3D) than their performances in the traditional classroom setting using the desktop computer (2D). Codier *et al*. presented a multi-user virtual environment (MUVE) that is based on the 3D interactive virtual collaboration platform Second Life ® for nursing education [49]. When using the MUVE, students can learn, interact, and collaborate in their avatar forms. Students' questionnaire interview showed promising results. It was found that majority of students commented that *(i)* learning activities in MUVE were fun and energizing; *(ii)* learning objectives can be achieved more interactively.

2.5 Key Elements of VR

Sherman and Craig described the key elements of a VR experience namely "a virtual world, immersion, sensory feedback (responding to user input) and interactivity" [25, 50].

2.5.1 Virtual World

A virtual world is a two-dimensional or three-dimensional space that is generated by a computer where users can interact with other people (avatar representation) and control/manipulate particular virtual objects in the virtual space. For example, a driving simulator contains both physical and virtual components. The physical components include the steering wheel, gas, and brake pedal, car dashboard, gears and display while the virtual elements contain the 3D virtual world (driving environment, road condition, weather, pedestrian, traffic. etc.). According to Muñoz *et al*., virtual worlds can be validated using appropriate usability heuristics [51]. The authors proposed 16 usability heuristics categorized into three main groups:

(1) Design and Aesthetics

- Feedback
- Clarity
- Consistency
- Simplicity

(2) Control and Navigation

- Orientation and navigation
- Camera control and visualization
- Low Memory Load
- Avatar's customization

- Flexibility and efficiency of use
- Communication between avatars
- Sense of ownership
- Interaction with the Virtual World

(3) Errors and Help

- Support for learning
- Error prevention
- Helps users to recover from mistakes
- Help and documentation

2.5.2 Immersion and Presence

Immersion is a psychological state when one's awareness is completely isolated from the physical surroundings but mentally or visually involved in a virtual environment or an imaginary space [52]. The sense of immersion is closely related to the term “suspension of disbelief"” or “willing suspension of disbelief,” which was introduced by the poet and aesthetic philosopher Samuel Taylor Coleridge in 1871 [53]. The term suggests the willingness to suspend one's belief in realism and believe the unbelievable. Unlike immersion, suspension of disbelief emphasizing on the effort from the creators of the virtual environment/movie/story to keep things believable and consistent. Sherman and Craig suggested that immersion can be categorized into two types: mental and physical immersion [50]. Mental immersion can be easily experienced through daily activities such as reading a book, hearing a story or watching a movie. When engaging in these activities, one can quickly feel he/she is part of the imaginary world and can isolate himself/herself from the physical surroundings. On the other hand, physical immersion requires the person to be physically active in an experience. Examples include a person playing a VR game with HTC Vive or a beginner learning how to drive a car in a driving simulator. These activities require participants to interact with the virtual objects in the scene by using different types of input devices or simply engaging their movements (motion tracking). Similar to Sherman and Craig's approach, Mount *et al*. introduced a simple taxonomy of immersion [54]. This taxonomy divides immersion into two categories: presence-based and engagement-based immersion. The presence-based immersion emphasizes the feeling of being mentally immersed or being there in the virtual scene while the engagement-based immersion describes a situation where a person feels engaged in the virtual world. The level of immersion can be affected by various senses such as visual, hearing, smell and touch. The visual level, including the field of view, display size and resolution, stereoscopy, and realism of lighting, tends to contribute more to the level of immersion than other senses [55, 56]. Other factors such as participants' interaction, the perception of self-movement, and control perception can also affect the overall level of immersion [52].

According to Slater, immersion deals with an objective experience using technology in the virtual environment [57]. Presence, on the other hand, is a "subjective experience of being in one place or environment" [52]. Presence is only quantifiable when the user is experiencing it [52, 57]. Witmer and Singer described four main factors that contribute to a sense of presence namely the control, sensory, distraction, and realism factor [52]. The control factor explains how much control that the participant has over specific tasks in a virtual environment as well as how natural the control mechanism is when interacting with the virtual objects or tasks in a virtual scene. The sensory factor deals with how well the sensory information is received while participating in a virtual environment. More specifically, it focuses on how much the multimodal information (e.g., movement, visual, auditory. etc.) from the environment involves the participant. The distraction factor is related to how much isolation can the virtual environment bring to the participant. In other words, it deals with participants' willingness to pay attention to the virtual environment stimuli and the number of distractions that participants may have. Lastly, the realism factor focuses on how well the virtual environment can represent the real-world environment. It must ensure that the information presented in the virtual environment is consistent with the real world. Based on these factors, Witmer and Singer created a set of questionnaires that can be used to measure presence in the virtual environment. In addition, they also developed an immersive tendency questionnaire (ITQ) to measure differences in the tendencies of individuals to experience presence. These questionnaires are helpful when evaluating the amount of presence that the participants experience in the virtual environment.

2.5.3 Sensory Feedback

Sensory feedback is an essential ingredient of VR for participants to be immersed in a virtual environment [25, 50]. In most cases, visual and aural feedback are generally more common to be experienced than other senses (e.g., smell, touch, and taste) in VR applications [58]. Touch feedback, also known as the haptic feedback, can also be presented with the introduction of haptic input device through vibration and pressure force. Smell and taste are the two senses that have not been commonly incorporated into VR applications, although humans tend to remember an experience more by scent than other senses such as sight, touch, or sound [59]. However, with recent progress in VR technology, we are fortunate even to experience the sense of smell in VR. For example, FeelReal Sensory Mask is a multisensory VR mask that can fully immerse users in a virtual environment by triggering their multiple sensory channels including smell and touch [60].

The device can provide different scents, wind flow, hot air, water mist, and vibration. It is mainly used as an add-on for popular VR headsets such as Oculus Rift and PlayStation VR.

It is imperative to reduce latency when receiving any types of sensory feedback from the virtual environment. For instance, a gesture-based input device, such as the Leap Motion controller, can track hand gesture/position and send this information to a computer for displaying a 3D virtual hand representation in real time. If a user visually experiences a significant delay in a virtual hand motion, it would not only reduce the sense of immersion but also result in poor performance in specific virtual tasks [61].

2.5.4 Interactivity

Interactivity connects the user and the virtual environment by allowing the user to directly take control of the virtual objects or tasks in the virtual environment using sensors or input devices. Because of the immersive and interactive nature of VR, information exchange can be done through multiple sensory channels such as hand gesture, voice, and auditory. Schomaker *et al*. and Hale and Stanney described a model illustrating the interactivity between human and virtual environments [62, 63]. The model implies a human-virtual environment interaction loop. The interface provides a flow of information between the human input channels and the computer output modalities. The human receives information from sensory channels (input) and performs actions based on the received information (output). Then the human output channels translate human actions into task-based actions into computer input modalities. Fig. 6 illustrates this interaction loop. From the research of Witmer and Singer and Straaten, interactivity can contribute to the sense of presence [52, 64]. Normal's research also found that when people are interacting with something, they are most likely to focus their attention and get involved [65]. In such a way, the interaction can strengthen people's attention and involvement [66], which essentially thought to be the two main components in enabling a sense of presence [52].

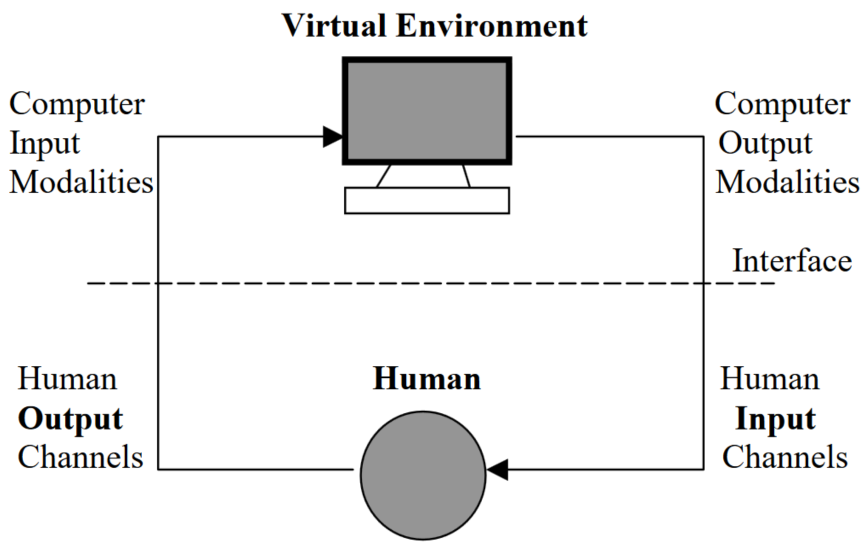


Fig. 6. Human-VE Interaction Loop from Schomaker *et al*. (1995) [62] and Hale and Stanney (2002) [63].

2.6 VR Technology in Education

Many studies have shown the success of VR technologies for education and training [67]. Experimental results suggest people can learn from VR simulations, achieving instructional effectiveness and the transfer of skills to the real world [7, 68, 69]. Moreover, VR-based laboratories are capable of supporting chemistry, physics, engineering, and surgical training sessions, providing a broad application across an entire range of disciplines.

There are a growing number of researches that have focused on the developments of virtual laboratories for distance learning programs [70-72]. Especially for manufacturing technology education, the instructional laboratories are an essential part of the program for students to learn complex systems and be familiarized with mechanical operations. However, it becomes a bottleneck to deliver such hands-on laboratory practices for engineering students who engage in distance learning programs. To tackle the challenges, a designed virtual reality software system, called VCIMLAB, was proposed in Bal's research to perform the virtual manufacturing laboratory for distance students [72]. It provides an interactive scene so that the students can have a sense of "being there." With interactions in the designed virtual environment, the students can feel what they are doing, instead of just watching things happening. The experimental results from Bal's research showed that the students who practiced with a virtual laboratory significantly outperformed those who were trained with conventional video demonstrations. It proves the developed VR-based laboratory was highly flexible and cost-effective on delivering a robotics laboratory experience to distance learning students. Most importantly, the VR-based laboratory provides a safe environment that students can learn from their mistakes without damaging machinery or harming themselves. Accordingly, it is highly regarded that VR systems are most suitable as a pre-training tool for those educational laboratories with highly expensive or potentially dangerous equipment so that the students can get familiar with operations and procedures from within the virtual environment in advance to avoid making crucial mistakes on the real equipment.

Compared with low-immersive VR, immersive VR gives the participant the perception of being physically present in the non-physical world, offering a very high potential in education since it makes learning more motivating and engaging. However, when it comes to "immersive VR in education," most of the research focused on the applications using CAVE-based environments, which are still rather expensive. This causes it to be very limited in application to education due to its high costs in devices and space. Lately, new devices like Oculus Rift and HTC Vive are superior to the CAVE-based approaches by its low costs and excellent transportability, making immersive VR possible to access in various educational situations [73]. Many educators have drawn attention to the usage of these kinds of VR headsets to carry out immersive VR in education. For example, a researcher at the University of Huddersfield utilizes VR headsets to provide accurate visualizations of human anatomy and surgical procedures [74]. The immersive VR environments have the capability of offering trainee surgeons with unrestricted, close-up 360-degree viewing, which is expected to contribute significant improvement to the operating room sessions in surgical training. Therefore, with better interactive scenes and vivid simulations that the participants can obtain from now low-cost immersive VR environments, we focus on the development of VR-based laboratories with higher levels of immersion.

CHAPTER 3

RELATED WORK

This chapter reviews a few relevant research and comments on the similarities and differences to the current study. To make the review more structured, this chapter focuses on investigating recent literature by categorizing these papers into two topics. The first topic covers that literature that studied the comparison of the learning effectiveness on different input devices or virtual reality platforms across various domains. The second topic describes recent literature which focuses on the development and evaluation of various interaction technique frameworks for virtual environments. The methodology and study results from the related literature, as well as similarity and differences to the current research, will be discussed.

3.1 Comparison of Capability/Learning Effectiveness on Various VR Platforms

In this section, we will discuss papers that compare capability and learning effectiveness on different virtual reality platforms. These literature provide insights on how to evaluate learning effectiveness along with other vital factors that might affect learning outcomes across different virtual reality platforms.

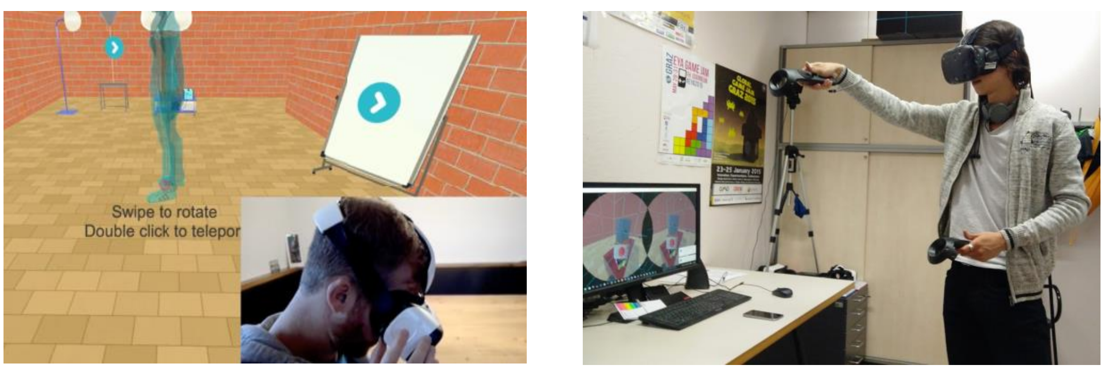
Kronqvist *et al.* proposed an efficient framework for assessing the authenticity of the virtual environment (VE) based on users' subjective experience [9]. This framework, based on Witmer and Singer's Presence Questionnaire (PQ) [52], was simplified as a shorter questionnaire which participants can quickly answer yet is detailed enough to offer rich qualitative data. The *authenticity index* was created from two different categories: (1) the level of immersion and (2) the level of control the participants experienced when working in the environment. The factors were measured to create the *authenticity index* are described in Table 3. In their study, participants were asked to do a few simple tasks such as interacting with virtual objects and navigating the virtual environment based on a virtual car model using three different devices, which were a headband, 3D glasses, and a head-mounted display (HMD). For assessing the *authenticity index*, a set of subjective questionnaires (with a 5-point Likert scale/Summated scale), was given to participants for measuring the degree of authentic VE experience covering the key factors including the level of immersion, control, and the side effects of simulator sickness. Afterward, the mean of the standardized VE *authenticity index* for those three devices was derived as the final factor that integrated those factors by applying principal component analysis (PCA) or factor analysis. The results showed that there was a significant difference between the HMD and the headband regarding authenticity index (level of immersion and control). No significant difference was found when comparing the headband and the 3D glasses.

TABLE 3

FACTORS USED TO CREATE AUTHENTICITY INDEX [9]

Category	**Factor**
Immersion	Feeling of presence Anticipated affordance compared to fulfilled affordance
Control	Feeling of control Discovery ratio Amount of technical problems experienced

Pirker *et al.* implemented a 3D virtual physics laboratory environment related to the Van de Graaff generator on a cost-effective mobile VR platform (Samsung Gear VR) and a room-scaled immersive VR platform (HTC Vive) [75]. Their study focused on investigating and comparing users' VR experience including factors such as engagement, immersion, learning, and user experience as well as usability across those two VR platforms. The evaluation was done by collecting users' subjective data based on a Game Engagement Questionnaire (GEQ) and a short list of interview questions. The results showed that both VR platforms provided participants with engaging and exciting learning experiences. Although participants generally felt more immersed, interactive and engaged in the room-scaled VR platform than its counterparts, regarding usability and users experience, a few participants experienced slight nausea when using the room-scaled VR platform. From their conclusion, when comparing to the mobile VR platform, the room-scaled VR platform can provide better interactions and a more immersive experience, which can be especially helpful for learning abstract physics concepts in the virtual environment. However, it is more cost-intensive and space-consuming. Although the mobile VR platform, on the other hand, has the advantages over the room-scaled VR platform regarding the cost and portability, it has drawbacks on the immersion level and advanced interaction.



(a) (b)

Fig. 7. 3D Virtual Physics Laboratory Experiment: (a) Mobile VR Platform and (b) Room-Scaled VR Platform [75].

Alhalabi designed a comparison study to evaluate the impact of different VR systems on students' learning performance in engineering related topics [76]. The author implemented three

VR platforms in this study: (1) a Corner CAVE System (2 walls) with 6 degree of freedom (6DOF) tracking (CCS), (2) HMD (Oculus Rift) with 6DOF tracking (HMD), and (3) HMD (Oculus Rift) without tracking (HMD-SA). The evaluation was done by giving a post-quiz to participants in each VR groups (CCS, HMD, HMD-SA) as well as an added control group (no VR). The study resulted demonstrated that the VR groups significantly outperformed the control group. However, no significant difference was found when comparing among the three VR groups, although the HMD group was superior over the other two VR groups (CCS and HMD-SA). This study also implied that a higher level of immersion and interaction might partially be the influencing factors in enhancing the learning performance in virtual environments.

(a) (b)

Fig. 8. Learning Engineering Topics with two VR Platforms: (a) A Corner CAVE System (CCS) and (b) A Head Mounted Display (Oculus Rift) with/without Tracking (HMD/HMD-SA) [76].

Kasireddy *et al*. developed a virtual construction environment on three different VR platforms, namely Oculus Rift VR, cardboard VR, and CAVE VR, for supporting related tasks regarding the construction project management [77]. They conducted a study to investigate which type of VR platform is suited for specific tasks such as information finding, navigation, and identification of unsafe scenarios in a virtual construction site. The study results implied that the CAVE VR is most suitable for tasks that require information finding spatially in a virtual environment as users can physically walk and look around the virtual information displayed on the walls of the CAVE. Regarding tasks that are related to navigation, the Oculus Rift VR is the best suited VR platform compared to the Cardboard VR (CAVE VR was not included due to technical issues) as it is more immersive with the more natural control mechanism. These research results provided insightful guidelines for project managers to select the appropriate VR solutions based on the nature of their application and budget requirement in support of construction project management. This study can also be extended to support similar tasks in other domains.

Kim *et al*. investigated and compared the effects of three different VR platforms, namely a regular desktop PC, a six-wall system with stereo screens (DiVE) and an HMD (Oculus Rift) on emotional arousal, task performance and simulator sickness [78]. They implemented the well-known Stroop effect task in a 3D virtual environment where participants were asked to find the 3D cards printed with words of different colors congruently (e.g., word of color and the color are matching) and incongruently (e.g., word of color and the color are not matching). The authors concluded that both the HMD and DiVE demonstrated significantly higher emotional arousal than the desktop PC. Regarding the task performance, HMD required longer total task time in both low-stress (congruent) and high-stress (incongruent) conditions. The HMD systems also induced the highest amount of simulator sickness among other two VR devices. This study provides useful insights on the benefits and limitations of using different VR devices in studies examining the emotional process and task performance, which may help developers and researchers efficiently select the appropriate VR solution for their future research.

3.2 Evaluation of Various Interaction Techniques in Virtual Environments

This section discusses and compares evaluation studies of various interaction techniques in virtual environments. These works of literature shed light on some of the advantages and disadvantages of using various input devices for completing certain interaction tasks in 3D virtual environments.

Ardito *et al*. compared the effectiveness of three low-cost input devices, namely the Xbox 360 gamepad, the Wii remote and the conventional keyboard and mouse combo, in performing simple interaction tasks in a 3D virtual environment [79]. The study was carried out by developing a 3D environment that contains two simple tasks such as rotation and navigation of a 3D virtual object. The authors compared the average time of completing these two tasks among three input devices. They concluded the gamepad is more efficient at rotation task; keyboard and mouse combo is better at navigation task. However, the difference is not substantial between the gamepad and keyboard and mouse. Wii remote, on the other hand, is the worst among the three input devices on both tasks. Their work also implied for simple tasks such as object rotation, the gamepad is preferred by most of the participants as the joystick on the controller offers a fast and easy way to rotate virtual objects. Pointing device such as Wii mote and mouse is not as efficient as the gamepad regarding the object rotation.

Cohé and Hachet experimented with comparing 3D manipulation techniques using the mouse and touchscreen [80]. The manipulation tasks included the rotation, translation, and scaling of a 3D cube (Fig. 9). They found that participants using the touchscreen are better at all tasks regarding response time and easiness compared with using the mouse. The difference is more significant with the scaling tasks between two interaction methods. However, in the translation task, although the touchscreen is slightly superior to the mouse, the difference is trivial. The study provides insights on how touchscreen interaction differs from mouse interaction for basic 3D manipulation tasks. However, one possible limitation of this study is that different screen sizes may affect the manipulation performance on touchscreens (e.g., smaller touchscreen devices such as smartphones or tablets).

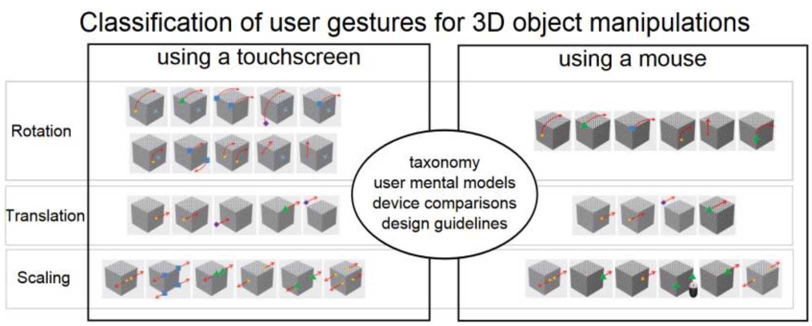


Fig. 9. Comparison of Interaction Tasks between Using a Touchscreen and a Mouse [80].

Zielinski *et al*. implemented a virtual reality application for training mine workers to learn safety issues in critical situations in a CAVE-typed virtual environment [81]. They compared participants' performances using three different interaction devices for various tasks such as selection, navigation, and maneuvering in a 3D virtual mining environment. They found that in the selection task, although a 6DOF of wand allowed participants to make selections significantly faster than a gamepad and an air mouse, it caused significantly more errors when the size of the virtual objects became smaller. In both the navigation and maneuvering task, participants were significantly faster when using the wand over the other two devices. This study indicated that from participants' subjective and objective data, the 6DOF wand is a more efficient interaction device for task completion in a 3D virtual environment. However, in a particular task such as selection, the wand provided the least accuracy when the virtual objects are smaller. The gamepad, although not as fast as the wand regarding the selection time, is significantly more accurate in the selection of small objects.

Dang *et al*. studied the interaction of four input techniques (*i.e.*, voice, 6 DOF wand, pen and sketch interfaces) across a series of tasks including scale, rotation, and translation of a 3D object for exploring 3D surfaces [82]. They found that among all the input devices, the voice interaction technique was the least accurate and took a significantly longer time to complete the task. On the contrary, the wand device was substantially faster than the other three input devices. Regarding accuracy, although the wand provided the least amount of errors, result analysis showed no significant differences among other input devices. From the qualitative results, the authors found that many participants favored the wand input device over the other three regarding usability (i.e., level of frustration, ease of use). The authors concluded that the 6DOF wand was more intuitive and efficient when performing basic manipulation tasks for 3D objects when compared with voice command, pen interface, and sketch method. However, one small concern of the wand device, based on subjects' comments, was that using the wand's zooming/scaling function excessively might cause wrist discomfort which may lead to a decrease of accuracy.

CHAPTER 4

METHODOLOGY

This chapter introduces the utility framework and describes how the framework is formulated from the ground level. In addition, it demonstrates how the framework is being applied by working through a use case. Lastly, it describes methods of validating and evaluating the framework.

4.1 Framework Formulation

In recent years, with the rapid development of technology and application in a virtual environment, a considerable amount of literature has started to focus on building frameworks that can provide general guidelines on designing activities, interactions, and applications in virtual environments. Schmeil *et al.* presented an avatar-based collaboration framework (ABC framework) that merges the collaboration patterns and learning objectives in a framework that specifically focuses on the collaborative and learning aspect [83]. These patterns are likely to result in more efficient uses of the virtual worlds medium, and thus may help designers plan out the collaboration and learning aspects in virtual worlds more effectively. Kim *et al.* introduced a conceptual framework containing three levels (interaction of users, immersive/visualization systems and collaborative tasks) to help users better understand social interaction in immersive systems and provide a guideline for supporting communication efficiently in visualization systems [84]. Zhu *et al.* formulated a conceptual framework that provides a guideline for developing augmented reality education applications [85]. The framework, based on three main layers (foundation, function, and outcome), emphasizes learning theories and integrates learning outcomes and objectives to support the development of augmented reality applications specifically for healthcare education. Bidarra *et al.* proposed a conceptual framework to help teachers and instructional designers select games, simulations and augmented reality environments specifically in mobile learning [86]. The framework is based on a six-dimensional operational model named ALDET, which includes issues related to availability and cost, interaction and communication capabilities, distance education workflow integration, learning design potential, engagement and ease of play, as well as thematic value and adequacy. Through these six steps, decision-makers can efficiently weigh the benefits and shortcomings of all the available choices. Cochrane *et al.* described a design-based research framework focusing on designing mobile virtual reality learning environments [87]. The framework includes four phases based on the learning design, design thinking, connections between theory and practice as well as intersections with mobile learning. While these kinds of literature provided general guidelines for designing applications on a specific type of virtual environment (*e.g.*, collaborative virtual environment, augmented reality, mobile virtual environment), none of them entirely focus on constructing a framework that can target on different types of virtual environment platforms. Thus, the current research aims to formulate a framework to serve as a reference guide for the educators and developers to efficiently decide on selecting an appropriate type of VR platform based on its software functionalities and hardware capabilities specifically targeting on interactive virtual laboratories.

4.1.1 Overall Framework Structure

The proposed framework is intended to avoid shortcomings of other existing frameworks, which only focus on one type of virtual environment or VR platform. The current framework is intended to tailor to various types of VR platforms from low immersive VR devices such as a mobile tablet to large-scale full immersive VR devices such as a CAVE. First, decision-makers or developers should identify what general interaction tasks are needed in the virtual laboratories they are intended to develop. Next, decision makers must specify the appropriate interaction techniques to manipulate virtual objects and to navigate in the virtual environment. To differentiate similarities and differences of various VR platforms, the last step is to examine their hardware and software properties and capabilities, including device portability, level of immersion, and so on. All these steps are illustrated in Fig. 10 with top to bottom approach.

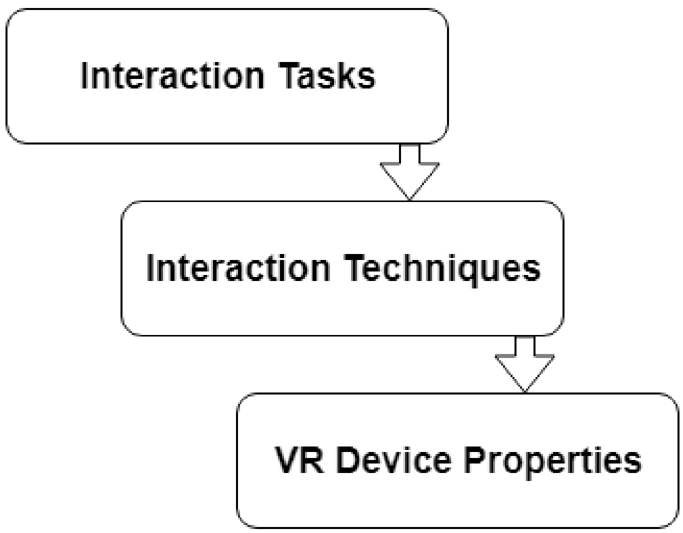


Fig. 10. Overall Framework Structure.

4.1.2 Interaction Tasks

As this framework is tailored to decision-makers and developers for selecting the best suited VR platform to implement virtual laboratories for engineering and science education, it is necessary to lay out a series of generic tasks and activities that are typically done in an engineering and science laboratory environment. Having a general description of these tasks can help decision-makers and developers further determine the proper interaction techniques in virtual environments more intuitively. Sanders *et al.* introduced a breakdown of typical laboratory tasks shown in Fig. 11 [88]. Tasks are organized into three categories: receive instruction, manipulate equipment, and inspect objects. Select and scroll are two general tasks that are typically performed when receiving and reviewing for laboratory instructions. Equipment manipulation consists of various tasks including selecting objects with high precision, turning a switch on and off, connecting wires and cables, and controlling certain scales or settings. When inspecting objects, there are tasks where users can zoom in the viewing perspectives and inspect the object in close detail or rotate the object and observe it from a different angle.

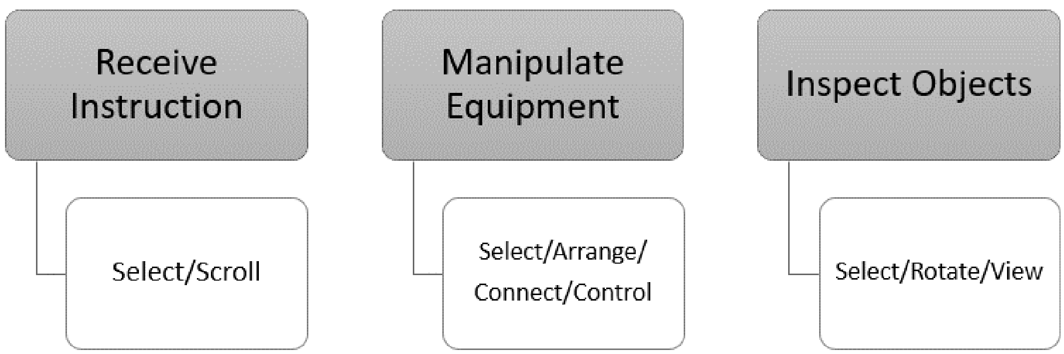


Fig. 11. Typical Laboratory Tasks Breakdown [88].

Based on the content from Fig. 11, interaction tasks in a laboratory environment are further refined and organized in Table 4. All tasks from three categories (*receive instruction*, *manipulate equipment*, and *inspect object*) from Sanders *et al.*'s work are now merged into the one section named *equipment/object manipulation*. These interaction tasks are simple enough for developers to make faster decisions, and yet generic enough to cover some of the representative laboratory tasks. These interaction tasks can also be virtualized in corresponding to *object manipulation* techniques in virtual environments.

TABLE 4

LABORATORY INTERACTION TASKS

	Equipment/Object Manipulation	Corresponding Virtualized Tasks
Interaction Tasks	☐ Tasks involve of moving components (e.g., wire connection, grabbing tools)	☐ Move (e.g., grab, drag and drop)
	☐ Tasks involve of decision making (e.g., push a button, select an object, switch on/off)	☐ Select (e.g., click)
	☐ Tasks involve of angular tuning (e.g., adjust knob-shaped object, steer wheel)	☐ Rotate
	☐ Tasks involve of translational tuning (e.g., balancing a scale by sliding a weight)	☐ Slide/scroll
	☐ Tasks involve of magnifying (e.g., observing objects in close detail)	☐ Resize

4.1.3 Interaction Techniques

A substantial amount of literature had exposures on summarizing and classifying interaction techniques in 3D virtual environments. The most predominant literature on such classifications is the taxonomy of selection and manipulation techniques from Bowman *et al*. [89] and taxonomy of virtual object manipulation techniques from Poupyrev *et al*. [90]. Bowman *et al*. break down interaction techniques into three main component branches: *selection*, *manipulation*, and *release*. Each branch is then decomposed hierarchically into a few subtasks. For example, selecting a virtual object (*selection branch*) involves the subtasks of providing a method to indicate an object (*object indication*), confirming its selection (*object selection*) and providing visual or audio feedback for specifying that the selection is accomplished (*feedback*). Poupyrev *et al*. used a different approach by categorizing interaction techniques based on two main interaction metaphors: *exocentric* and *egocentric*. In exocentric interaction, users interact with the virtual environment in a third-person view. Its sub-level contains world-in-miniature and automatic scaling. On the other hand, egocentric metaphor, which is often used in a more immersive environment, allows users to interact with the virtual environment from a first-person perspective. The two sub-levels of egocentric metaphor include virtual hand and virtual pointer metaphors.

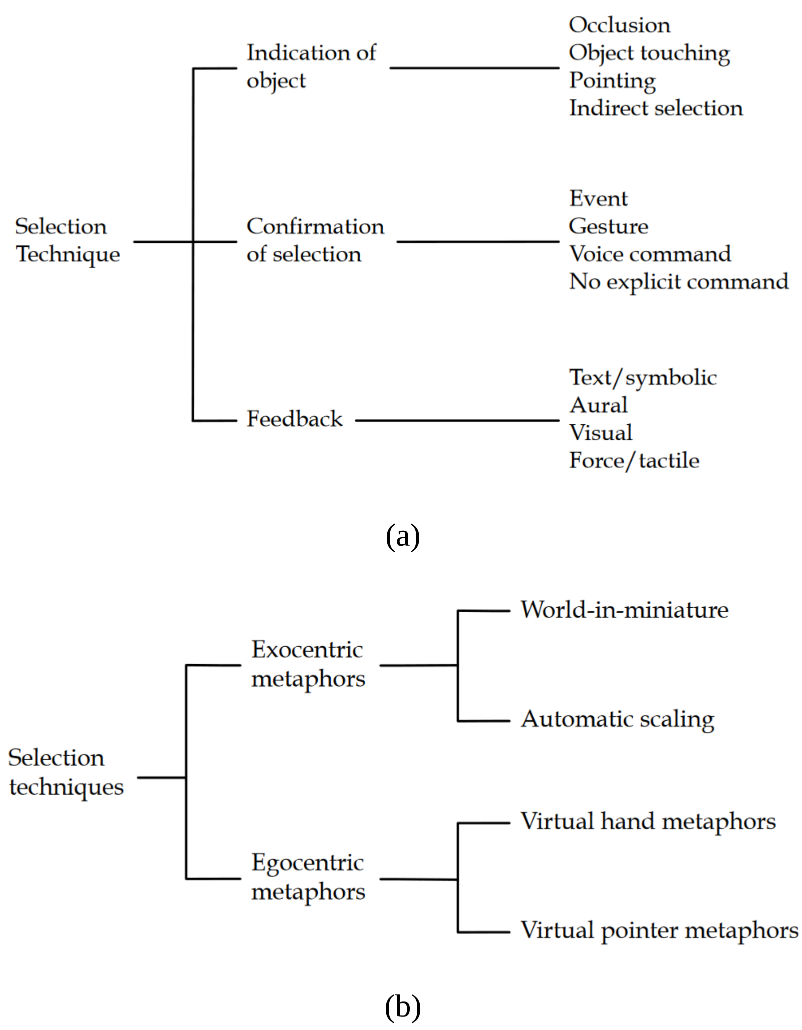


Fig. 12. Classification of Selection Techniques: (a) Bowman *et al* (1998) [89] and (b) Poupyrev *et al* (1999) [90].

Smith and Duke identified four main interaction techniques in VR, namely: *navigation*, *selection*, *manipulation*, and *environmental commands*. Navigation involves the techniques of exploring the 3D virtual world such as walking, running, and flying. Selection techniques refer to a virtual representation that is used to choose 3D virtual objects in the virtual environment. Examples could be a mouse cursor or an intersecting ray. Manipulation describes how virtual objects or tasks in the virtual environment can be controlled and carried out. This includes grabbing a virtual object or zooming in a camera. Environmental commands include drop-down menus, voice commands, and hand gesture commands. Compared with Bowman *et al*.'s techniques, *navigation* and *environmental commands* are added to diversify further the proposed interaction techniques related to traveling and giving commands in the virtual environment. However, Bowman *et al*. have already suggested a taxonomy dedicated to navigation and travel [91]. The classification method is also component-based with three main branches: *direction/target selection*, *velocity/acceleration selection,* and *input conditions*. Then each of these main branches is decomposed into several different sub-tasks, which are similar to Bowman *et al*.'s method of decomposition.

Based on this literature, a simplified interaction technique framework is formulated primarily based on Smith and Duke's interaction techniques that contain these components of *selection*, *manipulation, and navigation. Environmental commands,* including voice and gesture command, are merged into the *selection* techniques. The *object selection* section contains seven general selection representations (*cursor/pointer, 3D ray pointing, gaze-directed, direct touch, button approached, virtual gesture, and voice*), which include most selection techniques for various input devices across different VR platforms. For instance, *cursor/pointer selection* is primarily used in a PC mouse while *direct touch* is primarily utilized in touchscreens for mobile devices. The *object manipulation* section contains five main methods (*resize*, *rotate, move, select, and slide/scroll*). These techniques are virtualized for 3D virtual environments, and they are linked with generic laboratory interaction tasks from TABLE 4. *Resizing* allows users to scale the virtual object while *rotating* deals with the orientation of the virtual object in a 3D space. *Moving* virtual objects refers to positioning a virtual object to the desired location in a 3D space. *Selecting* is a method of choosing a specific virtual object to trigger or activate certain actions. *Sliding/scrolling* refers to moving particular objects along a designated straight path horizontally or vertically. There are two types of *navigation* techniques: *walk* and *teleport*. *Walking* refers to controlling a virtual character or avatar in either first-person or third-person view to moving from point A to point B with walking speed in a 3D virtual environment. *Teleport* refers to transport from one place to another in a 3D space instantly without the need to travel or navigate. All these findings are summarized in Table 5 below.

TABLE 5

INTERACTION TECHNIQUES IN VIRTUAL ENVIRONMENT

	Object Selection	***Object Manipulation***	***Navigation***
Interaction Techniques	☐ Cursor/pointer ☐ 3D Ray/beam pointing ☐ Gaze-directed ☐ Direct touch ☐ Button-approached ☐ Virtual gesture ☐ Voice control	☐ Resize ☐ Rotate ☐ Move (e.g. grab, drag and drop) ☐ Select (e.g. click) ☐ Slide/scroll	☐ Walk ☐ Teleport

4.1.4 VR Device Properties

This layer contains the basic properties and specification of a VR system. Decision makers will need to know the availability/accessibility of the desired VR system. Some VR devices are relatively easy to obtain including consumer electronics that can be easily purchased online/at the store. Some require special order or custom made such as specialized equipment – CAVE. Next, decision-makers should consider whether the VR device is portable enough to fit in the pocket or spacious enough to host multiple people for collaborative activities. Another factor to consider is the immersion level that is provided from the VR system display. Generally, there are two types of displays – stereoscopic displays and non-stereo displays. A stereoscopic display is also known as a 3D display, which is a pair of 2D offsets images that trick the brain into having a perception of 3D depth. A 3D display can increase a sense of presence [92]. Based on Alqahtani *et al*.'s work [24] mentioned in Section 2.4.1, a VR device can be categorized into three types: low-immersive, semi-immersive or immersive (full-immersive). Decision makers can then choose a VR device based on its level of immersion. The final step decision makers need to consider is how much they are willing to spend on a VR device as the price can range from under $100 to above $1000. These four dimensions (*accessibility*, *portability*, *immersion*, and *cost*) are organized in TABLE 6 below.

TABLE 6

BASIC PROPERTIES OF VR DEVICES

Accessibility	☐ Easy (e.g. consumer electronics) ☐ Medium (e.g. requires special order) ☐ Difficult (e.g. specialized equipment)
Portability	☐ Not portable ☐ Semi-portable (e.g., medium size, can be carried with both hands) ☐ Portable (e.g., pocket size, or can be easily carried around in a small bag)
Immersion	☐ Low (e.g., non-stereo screen) ☐ Partial (e.g., stereo screen, but not completely isolate you from the real world) ☐ Full (e.g., stereo screen, such as VR headset, fully immerse the user in a virtual world)
Cost	☐ Low ($0 ~ $500) ☐ Moderate ($500 ~ $1200) ☐ High (above $1200)

4.2 Framework Use Case: Jet Impact Force on Vanes

The proposed framework is applied for selecting the most suited VR system for the Jet Impact Forces on Vanes (Jet-force) experiment in one of the undergraduate level laboratory courses (MAE 305 Thermal-fluids Laboratory) at Old Dominion University in Norfolk, Virginia. To prepare for the physical-to-virtual transformation of a laboratory experiment on a suited VR platform, the first step is to determine what procedure and types of tasks are needed to complete the whole experiment. In the Jet-force experiment, most of the tasks involve decision making (e.g., selecting virtual equipment), translational tuning (e.g., sliding the weight to balance the ruler scale), and magnifying (e.g., observing the readings on the scale in close detail). Thus, these interactions can be then virtualized such as selecting, sliding/scrolling, and resizing. For navigation, the teleport option will be used in this virtual laboratory as it is time-saving to switch the camera view to a specific working area instantly other than walking in the virtual environment. After refining all the requirements of fundamental properties of the VR platform and interaction tasks of the virtual laboratory, decision-makers and developers can mark each item based on their conditions as shown in TABLE 7.

Once all the requirements are marked from Table 7, they will be mapped to a new table (shown in TABLE 8), which lists five representative VR devices (in rows) ranging from low-immersive to full-immersive systems along with their software and hardware capabilities (in columns). TABLE 8 also lists the ground truth of each VR system across different categories.

TABLE 7

APPLYING THE JET-FORCE EXPERIMENT EXAMPLE USING THE UTILITY FRAMEWORK

<table>
<tr><th rowspan="2">Interaction Tasks</th><th colspan="3">Equipment/Object Manipulation</th></tr>
<tr><td colspan="3">☐ 1.Tasks involve of moving components (e.g., wire connection, grabbing tools)
☒ 2.Tasks involve of decision making (e.g., push a button, select an object, switch on/off)
☐ 3.Tasks involve of angular tuning (e.g., adjust knob-shaped object, steer wheel)
☒ 4.Tasks involve of translational adjustment (e.g., balancing a scale by sliding a weight)
☒ 5.Tasks involve of magnifying (e.g., observing objects in close detail)</td></tr>
<tr><th rowspan="2">Interaction Techniques</th><th>Object Selection</th><th>Object Manipulation</th><th>Navigation</th></tr>
<tr><td>☒ 6.Cursor/pointer
☒ 7.3D Ray/beam pointing
☐ 8.Gaze-directed
☐ 9.Direct touch
☐ 10.Button-approached
☐ 11.Virtual gesture
☐ 12.Voice control</td><td>☐ 1.Move (e.g. grab, drag and drop)
☒ 2.Select (e.g. click)
☐ 3.Rotate
☒ 4.Slide/scroll
☒ 5.Resize</td><td>☐ 13.Walk
☒ 14.Teleport</td></tr>
<tr><th rowspan="4">VR Device Properties & Capabilities</th><th>Accessibility</th><td colspan="2">☒ 15.Easy (e.g. consumer electronics)
☒ 16. Medium (e.g. requires special order)
☐ 17. Difficult (e.g. specialized equipment)</td></tr>
<tr><th>Portability</th><td colspan="2">☐ 18.Not portable
☒ 19.Semi-portable (e.g., medium size, can be carried with both hands)
☒ 20.Portable (e.g., pocket size, or can be easily carried around in a small bag)</td></tr>
<tr><th>Immersion</th><td colspan="2">☐ 21. Low (e.g., non-stereo screen)
☒ 22. Partial (e.g., stereo screen, but not completely isolate you from the real world)
☒ 23. Full (e.g., stereo screen, such as VR headset, fully immerse the user in a virtual world)</td></tr>
<tr><th>Cost</th><td colspan="2">☐ 24. Low ($0 ~ $500)
☐ 25. Moderate ($500 ~ $1200)
☐ 26. High (above $1200)</td></tr>
</table>

TABLE 8

UTILITY FRAMEWORK USE CASE RESULTS

	Input Method	Interaction			VR Device Properties				Score
		Selection	***Manipulation***	***Navigation***	**Accessibility**	**Portability**	**Immersion**	**Cost**	
Mobile Device (smartphone & tablets)	Finger	Direct touch + 0 point	Good for: **Resize** Rotate Move **Select** **Slide** + 3 points	Good for: **Teleport** + 1 point	**Easy** + 2 points	**Portable** + 2 points	**Low** + 0 point	**Low** + N/A point	**8**
Desktop PC & Laptop	Keyboard & Mouse	**Cursor/pointer** Button-approached + 1 point	Good for: **Resize** Move **Select** **Slide** + 3 points	Good for: **Teleport** Walk + 1 point	**Easy** + 2 points	**Semi-Portable** + 2 points	Low + 0 point	**Moderate** + N/A point	**9**
Virtual 3D Tablet & Immersive Desk (Z-Space)	Stylus (6DOF)	**Cursor/pointer** **3D Ray-pointing** + 2 point	Good for: **Resize** Move **Select** **Slide** + 3 points	Good for: **Teleport** + 1 point	**Medium** + 2 points	**Semi-Portable** + 2 points	**Partial** + 2 points	**High** + N/A point	**12**
VR Headset (Oculus Rift)	Oculus Touch, Gaze Directed	**3D Ray-pointing** Gaze-directed + 1 point	Good for: **Resize** Rotate Move **Select** **Slide** + 3 points	Good for: Walk + 0 point	**Medium** + 2 points	**Semi-Portable** + 2 points	**Full** + 2 points	**Moderate** + N/A point	**10**
CAVE	Joystick, Gamepad	Button-approached + 0 point	Good for: **Resize** **Slide** + 2 points	Good for: Walk + 0 point	**Difficult** + 0 points	**Not portable** + 0 points	**Full** + 2 point	**High** + N/A point	**4**

4.2.1 Weight Assignment

For this framework, the goal is to design a recommendation system that suggests the most suited VR device to meet the users' design requirements for their VR applications. The suggested VR device is supposed to be based on the matching level between the users' requirements and the properties/capabilities of each VR device. However, VR developers and decision makers must consider various factors for different scenarios before the development process takes place. These factors should have a priority which depends on users' overall consideration for each scenario. That means the most suited candidate is not necessarily the most matching VR device through global optimization. Therefore, this designed framework applies the *score of suitability* that considers weight, rather than a matching score, to reflect the users' overall needs.

In the Jet-force experiment user case, decision makers describe the requirements for their VR applications via questionnaire. To observe the users' needs and priorities for different factors, all question items can be labeled accordingly in check-boxes that allow multiple selections. The hypothesis is that if a decision maker made multiple selections of a category, it in some way can reflect users' flexibility in that specific category, which is inversely proportional to the priority. Taking the cost factor as an example: if a single choice of "*low*" cost option is marked, the budget is expected to be limited. The priority (weight) for the cost factor is expected to be high (increased) because of the limited budget. If a decision maker selects a single choice of a "*moderate*" cost option, it may imply that the decision maker is only interested in mid-tier VR devices but has no interests in any low-tier VR devices. A high priority should also be given in this scenario. On the contrary, if the decision maker selects both of the "*low*" and "*moderate*" cost options simultaneously, it may suggest that the current budget is adequate (but still limited) and low-tier VR devices are also acceptable options. Thus, the decision maker has more flexibility in choosing their VR devices. Besides, more selections suggest more types of VR devices will meet the criteria and become potential candidates. Therefore, a lower weight should be assigned since the user is not very strict with the budget requirements. Finally, an extreme case is that all three items ("*low*", "*moderate*", and "*high*") in cost are selected. This implies that the budget is not a concern (out of consideration), and all VR devices from every tier can be considered for this scenario. In this case, the priority for the cost factor is the least, and the lowest weight should be assigned. As a result, the weight assignment is designed based on the user selection: if a user picks all *3 items = 1 weight point*, *2 items = 2 weight points*, *1 item = 3 weight points*. The more picked items result in a lower weight since more VR devices can be taken into considerations. In terms of the matching level, it either hits (1 point) or does not hit (0 points). In other words, as long as one of the ground truths are matching with any of the user selections, then the matching point is 1 point (equivalent to the "OR" relationship). The equation is described as: *score of suitability = matching level * priority weight*.

As an example to demonstrate the *score of suitability* equation, TABLE 9 below shows the ***portability*** factor in mobile devices comparing the ground truth with the user selection under different scenarios.

TABLE 9

THE SCORE OF SUITABILITY EXAMPLE (PORTABILITY IN MOBILE DEVICES)

Ground Truth	User Selection
☐ 18.Not portable	☒ 18.Not portable
☐ 19.Semi-portable	☒ 19.Semi-portable
☒ 20.Portable	☐ 20.Portable

In this case, nothing is matching. The score of suitability is:
*0 points * 2 weight points =* ***0 points***

Ground Truth	User Selection
☐ 18.Not portable	☒ 18.Not portable
☐ 19.Semi-portable	☒ 19.Semi-portable
☒ 20.Portable	☒ 20.Portable

One ground truth is matching with one of three user selections. The score of suitability is:
*1 point * 1 weight points =* ***1 point***

Ground Truth	User Selection
☐ 18.Not portable	☐ 18.Not portable
☐ 19.Semi-portable	☒ 19.Semi-portable
☒ 20.Portable	☒ 20.Portable

One ground truth is matching with one of three user selections. The score of suitability is:
*1 point * 2 weight points =* ***2 points***

Ground Truth	User Selection
☐ 18.Not portable	☐ 18.Not portable
☐ 19.Semi-portable	☐ 19.Semi-portable
☒ 20.Portable	☒ 20.Portable

One ground truth is matching with one user selection. The score of suitability is:
*1 point * 3 weight point =* ***3 points***

The *score of suitability* equation only applies in the third section of the framework "*VR Device Properties*," as demonstrated in TABLE 8. Each marked box represents 1 point in the first two sections. All the score will be added for each row. The highest score will be taken into consideration of determining the most suitable VR device for the Jet-force virtual laboratory. In this use case, the Z-Space has the highest score, followed by the VR headset. Thus, those two devices are the top two suited VR platforms for the Jet-force virtual experiment based on its tasks, interactions and hardware requirements. If there is a tie with the score, the following table (TABLE 10), containing the advantages and disadvantage of VR devices can further help decision-makers to weigh their options.

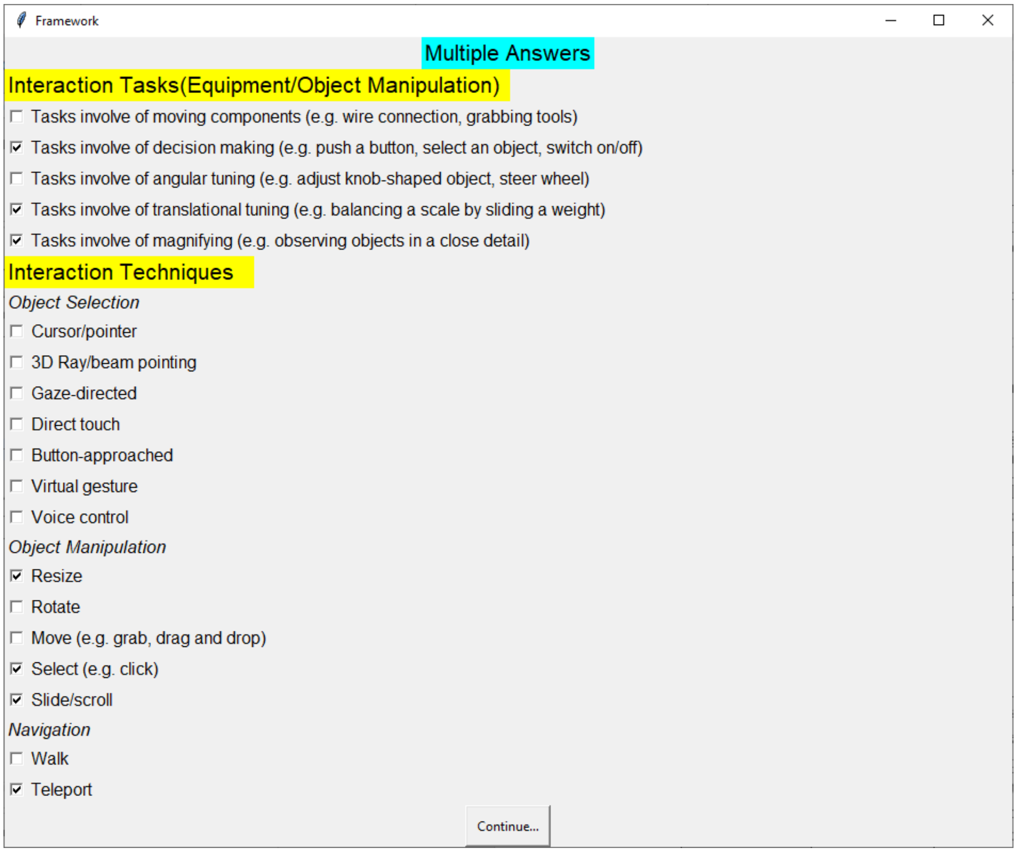
TABLE 10

PROS AND CONS OF VARIOUS VR DEVICES

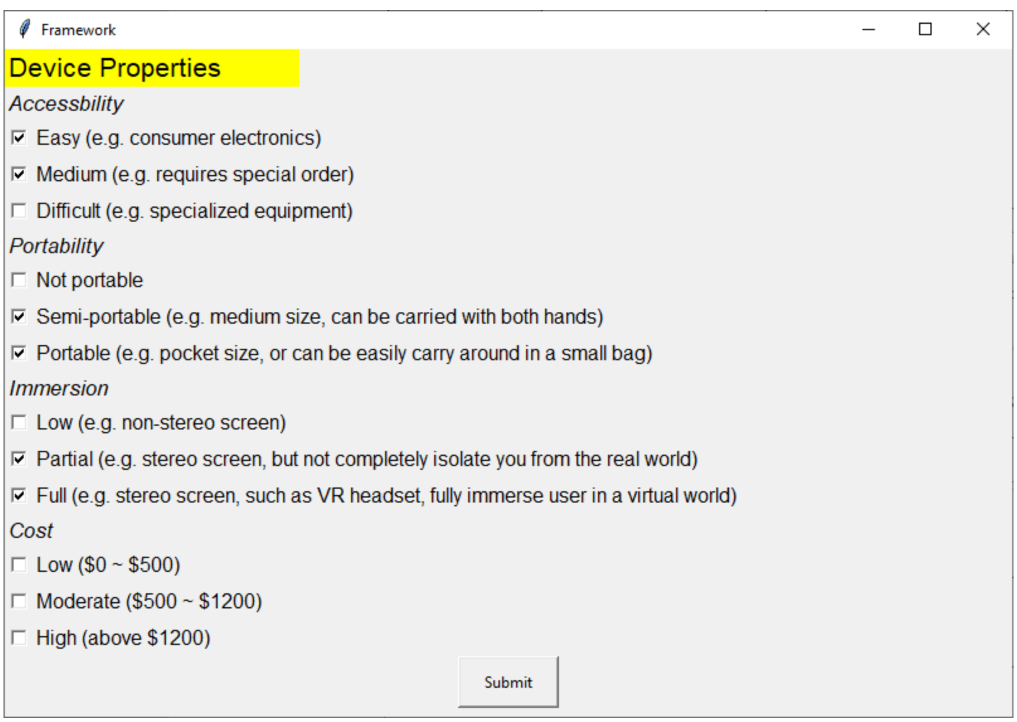
	Advantage	**Disadvantage**
Mobile Devices (smartphone & tablets)	Portability	Small display size, less immersion
Desktop PC, Laptop Devices	Easily accessible	2D mouse cursor is not ideal when doing spatial tasks that have depths in 3D environments
Z-space	Raycasting of the stylus provides accurate pointing. Tracking headset allows participants to observe the virtual objects in 360 degrees.	First person navigation in the virtual environment is very limited
VR Headsets	Full immersive experience. Easy to navigate in the virtual environment.	May cause simulation sickness.
CAVE	Spacious - can have multiple people working in the virtual environment together	Not portable. Participants need to meet at the location of the CAVE physically. The facility is also expensive to maintain.

4.3 Software-based Framework

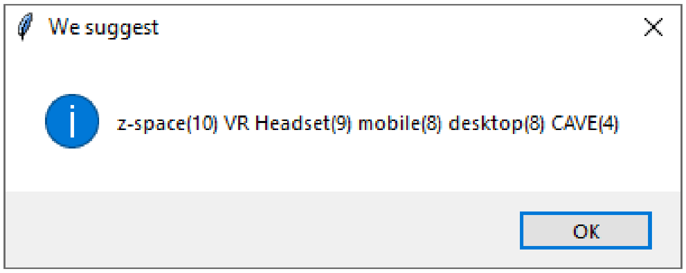
To simplify the procedure of using the table-based framework, a software-based framework with a graphical user interface (GUI) is implemented using Tkinter in Python. Users can pick their desired options using the GUI, and the software will display the suggested result based on users' selection immediately. The scoring system was integrated and programmed into the software, and the *score of suitability* equation was computed automatically based on the users' selections. The software-based framework offers users a convenient way to see and analyze a "what-if" scenario. Fig. 13 illustrates the software-based framework GUI. The selections are corresponding to the ones from the table-based framework. The final result from the software-based framework demonstrates the final score from each VR device in descending order. The result matches with the table-based framework.


Framework
Multiple Answers
Interaction Tasks(Equipment/Object Manipulation)
Tasks involve of moving components (e.g. wire connection, grabbing tools)
Tasks involve of decision making (e.g. push a button, select an object, switch on/off)
Tasks involve of angular tuning (e.g. adjust knob-shaped object, steer wheel)
Tasks involve of translational tuning (e.g. balancing a scale by sliding a weight)
Tasks involve of magnifying (e.g. observing objects in a close detail)
Interaction Techniques
Object Selection
Cursor/pointer
3D Ray/beam pointing
Gaze-directed
Direct touch
Button-approached
Virtual gesture
Voice control
Object Manipulation
Resize
Rotate
Move (e.g. grab, drag and drop)
Select (e.g. click)
Slide/scroll
Navigation
Walk
Teleport
Continue...

(a)


Framework
Device Properties
Accessbility
Easy (e.g. consumer electronics)
Medium (e.g. requires special order)
Difficult (e.g. specialized equipment)
Portability
Not portable
Semi-portable (e.g. medium size, can be carried with both hands)
Portable (e.g. pocket size, or can be easily carry around in a small bag)
Immersion
Low (e.g. non-stereo screen)
Partial (e.g. stereo screen, but not completely isolate you from the real world)
Full (e.g. stereo screen, such as VR headset, fully immerse user in a virtual world)
Cost
Low ($0 ~ $500)
Moderate ($500 ~ $1200)
High (above $1200)
Submit

(b)



(c)

Fig. 13. Software-based Framework GUI: (a) Interaction Tasks and Techniques, (b) VR Device Properties, and (c) Final Result.

4.4 Framework Validation

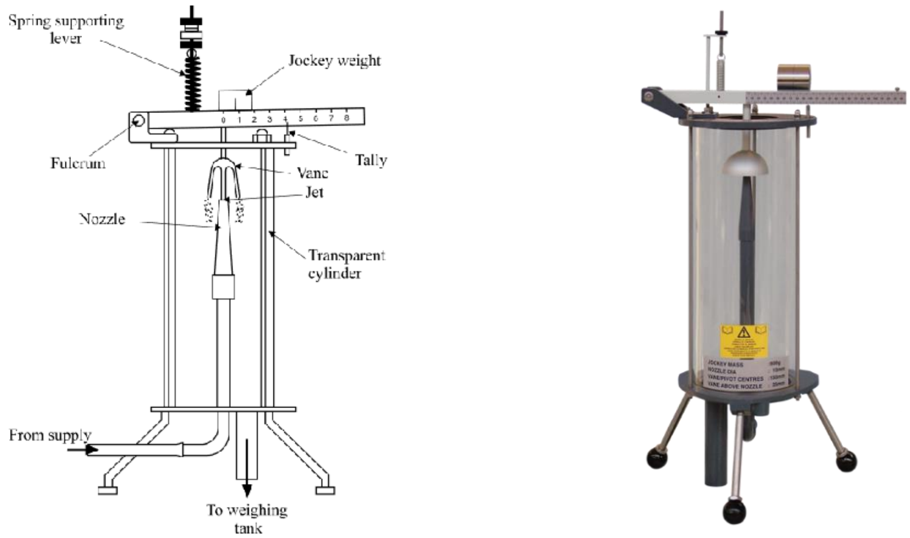
To further validate the utility framework, a research study targeting participants' general performance on all five VR platforms is needed. The evaluation and validation consist of both quantitative and qualitative assessments. The quantitative assessment is based on the statistical analysis of participants' quantified survey questionnaire results (subjective) and direct observation data (objective). On the other hand, the qualitative assessment includes participants' pre- and post-interview questions regarding their subjective user experiences with the VR platforms.

4.5 Jet Impact Force on Vanes: Design and Implementation

This section describes the background and apparatus of the Jet Impact Force on Vanes (Jet-force) experiment. It also discusses the design and implementation process of virtualizing the experiment across five VR systems (mobile device, desktop PC, immersive 3D tablet (Z-Space), VR headset (Oculus), and CAVE) ranging from low-immersive to full-immersive.

4.5.1 Experiment Apparatus

The overall objective of the experiment to determine the jet impact force of a reversal water jet hitting on a type of vane, which is a flat-shaped or a funnel-like shaped object with a narrow mouth (both vanes have narrow stems). The equation $F = C\dot{m}^n$ represents the relationship between force (F), mass flow rate ($\dot{m}$) and type of vane (C). Initially, a type of vane needs to be attached to a jockey-weight sliding scale that is mounted on top of the cylindrical lid. When the equipment is powered on, water is discharged through a nozzle inside of a transparent cylindrical storage tank to form a jet, thus providing an impact force on the selected vane. The water jet flow speed can be set to three levels (low, medium or high mode) by adjusting a water valve. As the flow speed changes, the force from the water jet deflects the beam from a horizontal position. Hence, the jockey-weight can be slid along the beam to ensure the beam is balanced. The indication of a balanced beam is represented by a blue tally line not exceeding the top surface of the cylindrical lid. As the water jet continues to hit the vane, water falls to the bottom tank for re-circulation. Mass flow rate is then measured with a stopwatch by collecting a given amount of mass over time. The similar procedure can be repeated with a different shape of a vane to observe how the jet impact force is affected by the mass flow rate. Fig. 14 shows the 2D illustration and the physical setup of the top half section of the Jet-force experiment setup.



(a) (b)

Fig. 14. Jet-force Experiment Setup (top): (a) 2D Illustration and (b) Physical Setup.

4.5.2 Previous Work

The physical-to-virtual transformation of this experiment was done from a previous study with emphasis on comparison and evaluation of the learning effectiveness across two VR system setups namely the 3D TV and the CAVE [3]. The virtual modules replaced the traditional paper-based pre-lab manual for students to learn and practice before their experiment on the physical equipment. During the virtual module pre-lab session, students were asked to review the virtual experiment instructions within the first five minutes, and then they walked through the virtual experiment step by step by using a wireless Xbox gamepad as the input device. Study results revealed that students with the 3D interactive virtual modules (3D TV and CAVE) outperformed the control group significantly in their average post-quiz scores based on the fundamental knowledge of the experiment concept and procedure. However, no significant difference was found between the 3D TV and the CAVE group. Thus, it was concluded that virtual modules were effective as a pre-lab learning tool. Students also commented that virtual modules provided them with more interactivity and engagement to practice and familiarize with the laboratory procedure. Fig. 15 illustrates the setup of the 3D virtual Jet-force experiment on the 3D TV and the CAVE, respectively.

Fig. 15. Virtual Jet-force Experiment on the 3D TV (Left) and the CAVE (Right) System.

4.5.3 Current Work

The current work aims to design and implement the same Jet-force experiment across five representative VR systems (mobile, desktop PC, 3D stereo tablet (Z-Space), and CAVE) ranging from low-immersive to full-immersive. Fig. 16 describes the taxonomy of these VR systems based on the level of immersion, modified from Muhanna [25]. This process includes migrating previous work from the outdated game engine 3DVIA Virtools to a new game engine Unity. All the game logic design and user interface will be reworked and started from scratch in Unity. In addition, the current work carries out a research design emphasizing on evaluation and comparison of participants' subjective experiences on different VR systems including key factors such as immersion, control, concentration, emotion, and comfort. These results will be used to validate the results from the designed utility framework.

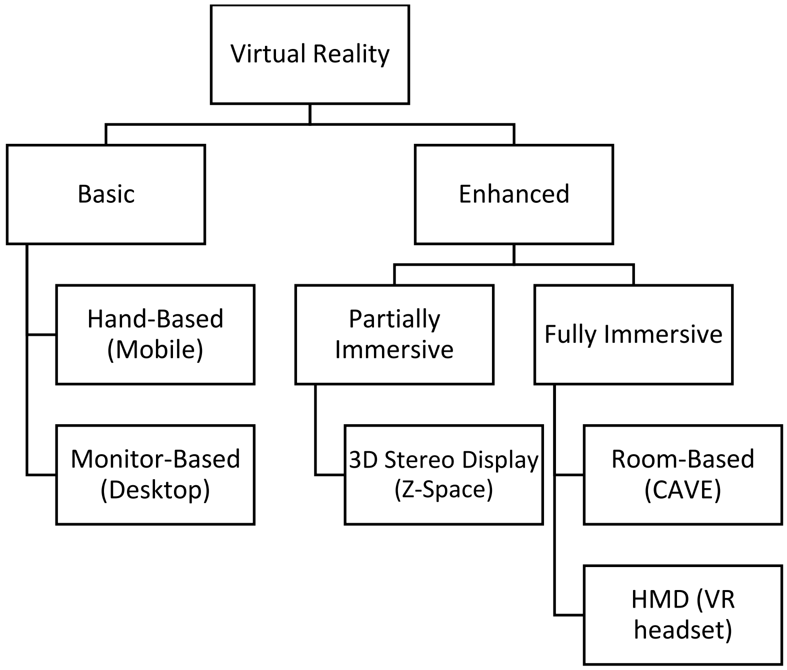


Fig. 16. Taxonomy of Five Representative VR Systems based on Immersion Level.

4.5.4 Design and Implementation

The design process of a VR application involves three main steps. The first step is to acquire all the necessary 3D models and textures and import them to the game engine Unity. The next step is to build functionality in Unity. This is a crucial step because it develops the core framework and functionality of the application such as animations, simulations, and interactions. Game logic design and user interface design will also take place in this step. The last step is to deploy the build files to the desired VR system. Fig. 17 describes the design workflow of a VR application.

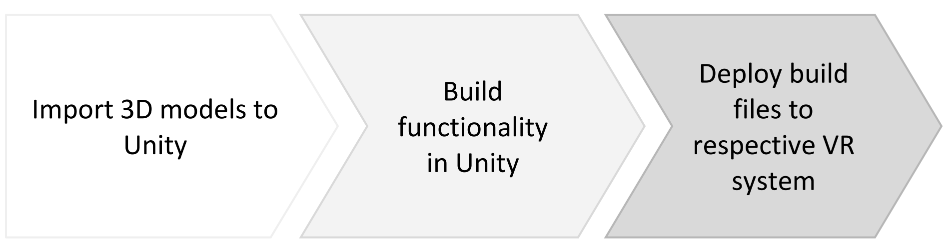


Fig. 17. VR Application Design Workflow.

Conceptual Architecture

Fig. 18 illustrates the conceptual architecture of the Jet-force lab. The Jet-force lab framework and core components contain all the necessary assets that are imported and programmed in Unity to realize the simulation and interaction of the Jet-force lab application. Build setting includes desktop and Android applications. The Desktop application can be deployed to Oculus VR application, CAVE application and the Z-Space application, with the integration of the VRTK, MiddleVR, and Z-Core development (SDK) toolkit, respectively. The Android application can be deployed to the mobile application with the Java Runtime Environment and Android SDK package.

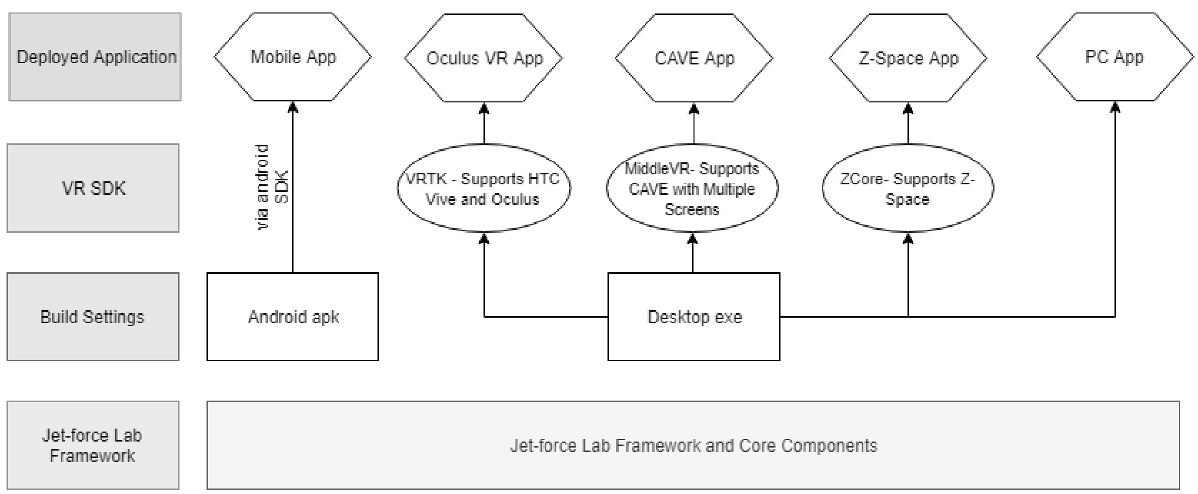


Fig. 18. Conceptual Architecture of the Jet-force Lab.

Core Component Library

The core component library contains all assets of the Jet-force laboratory applications including 3D models and 2D sprites, sound effect controller, simulation logic system, GUI system and even handler, user input controlling system and user view controlling system. Fig. 19 illustrates the core component library in a block diagram form.

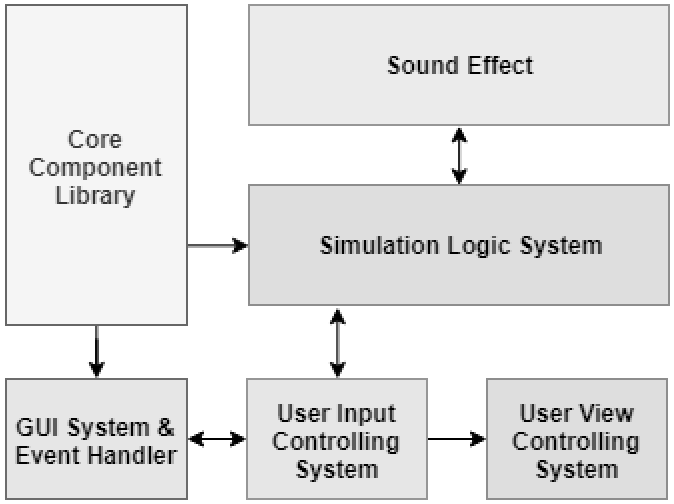


Fig. 19. Core Component Library Diagram.

The following paragraph explains each functional block in detail:

- **Simulation Logic System** simulates the control logic of the 3D virtual Jet-force equipment. It updates the simulation based on the current state of the Jet-force components such as the status of the visual outputs represented by the particle system (e.g., fluid particles) or virtual physics (e.g., 3D rigid body).
- **Sound Effect** includes audio files such as equipment audio effect and background music associated with the applications.
- **User Input Controlling System** builds the interaction for the user to manipulate the virtual objects in the application using a respective input device.
- **User View Controlling System** contains five different perspective views focusing on different working areas of the virtual Jet-force equipment. Users can quickly teleport to the corresponding view to work on a specific task.
- **GUI Menu System and Event Holder** provide a comprehensive graphical user interface along with a 2D UI menu system. It also manages various events in the application.

Graphical User-Interface Design

Graphical User Interface (GUI) builds the interaction between the application and input device controlled by the user. The design of a GUI should be user-friendly and simple enough for first-time users to understand and access. As this application is targeted at engineering laboratory settings, the GUI should be aesthetically integrated with the educational theme. Thus, a gradient light blue color is used as the background since it highlights the white graphical icons (as illustrated in Fig. 20 below).

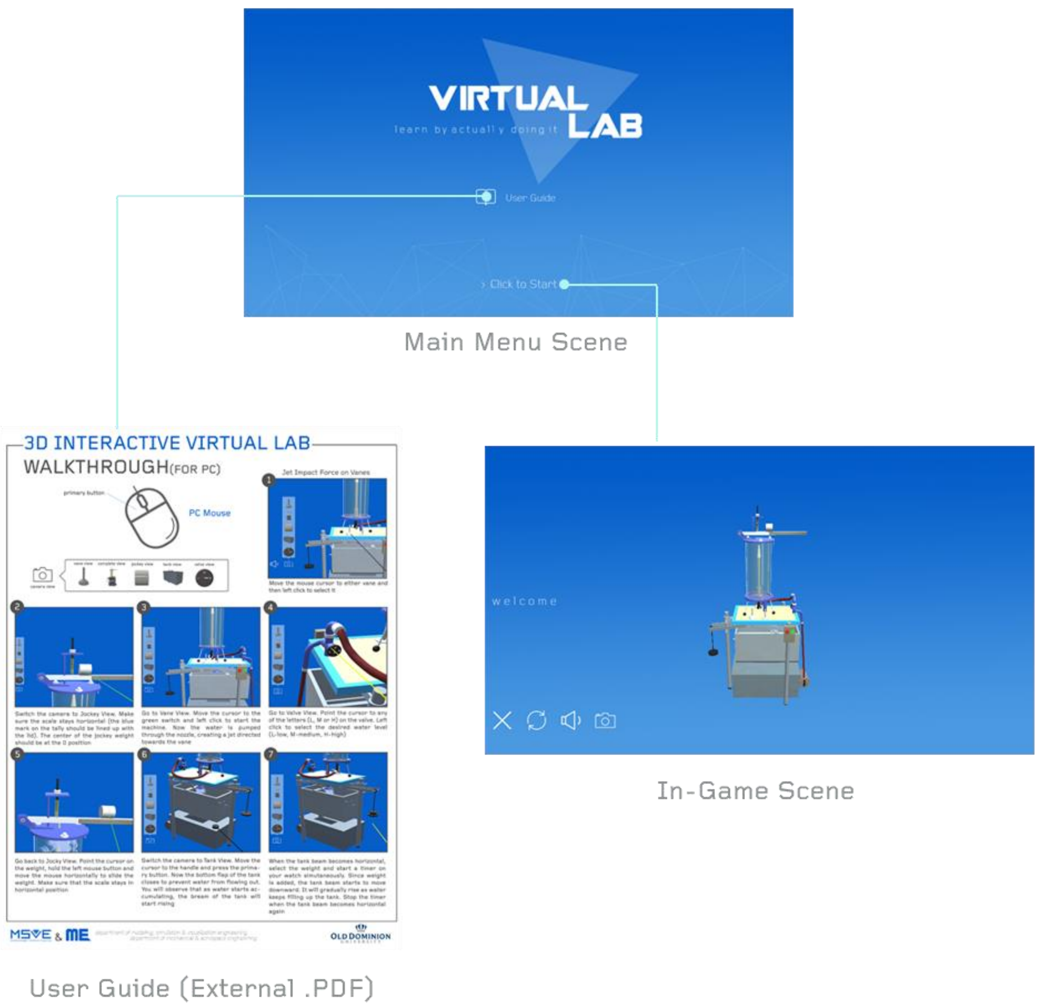
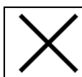
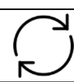
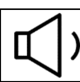


Fig. 20. Jet-force Experiment Application Wireframe (Three Main Scenes).

Fig. 20 illustrates three primary scenes for the Jet-force experiment application. When the application is launched, main menu scene is a start scene that allows users to either begin the virtual experiment by clicking on “the Click to Start” icon or check the experiment tutorial guide by clicking on the “User Guide” icon. The user guide scene enables users to walk through the experiment tutorial before starting the virtual experiment. Lastly, the experiment scene (in-game scene) carries out the virtual experiment simulation where users can interact with the virtual equipment to go through the whole experiment process. The white outlined UI icons on the lower left corner of the in-game scene contain the following commands: exiting the application, restarting the experiment, toggling sound on/off, and switching user views. The description is illustrated in TABLE 11.

TABLE 11

ICON COMMAND DESCRIPTION IN THE EXPERIMENT SCENE (IN-GAME SCENE)

			
Exit	Restart	Sound	View

User View Design

The Jet-force experiment application is designed to have a total of five viewing angles/perspectives to focus the in-game camera on a few specific locations of the 3D Jet force equipment. This view switch feature, also known as the navigation method “teleport,” can quickly locate the camera to a designated or preset position for users to complete a specific experiment task without having to manually “walk” to that location. The default view is set to the “complete view” at the start of the experiment. Other views include the “jockey view,” “valve view,” “vane view," and "tank view." Fig. 21 illustrate all the viewing perspectives in the experiment in a wireframe mode. When users select the camera icon on the lower left screen, a new menu containing all five views will appear to offer users the capability of switching to the desired view.

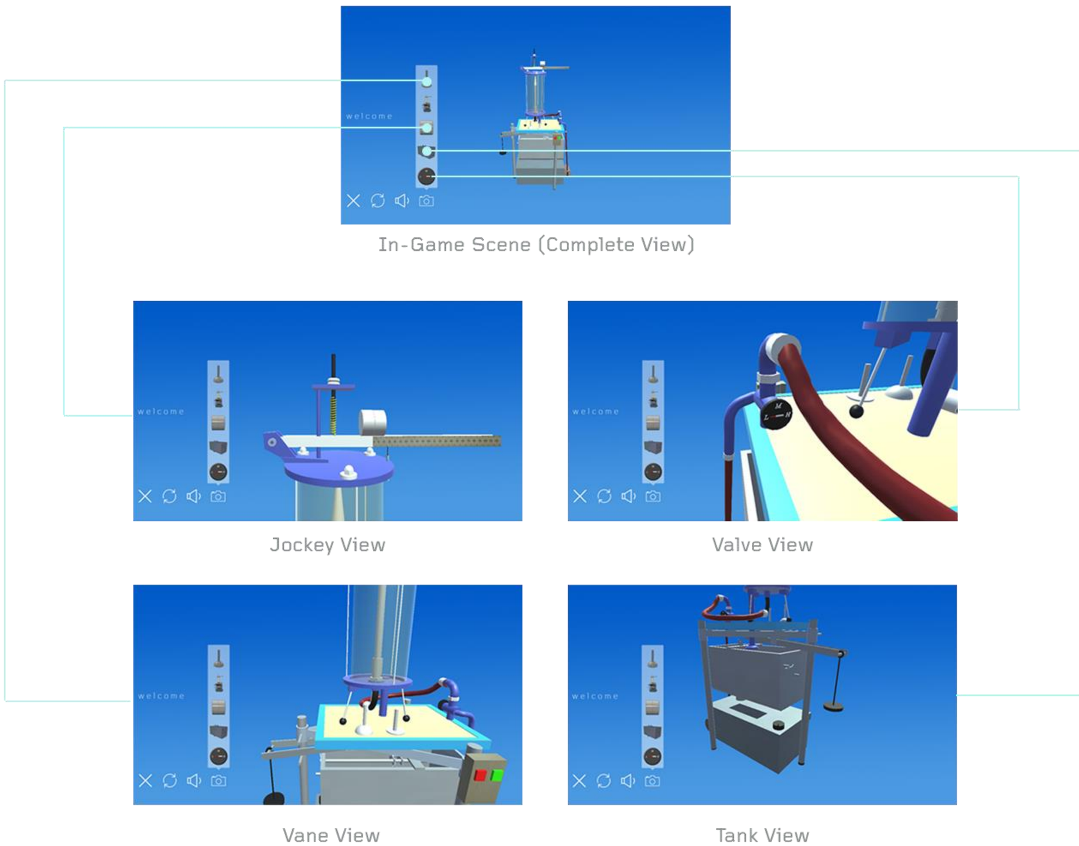


Fig. 21. Wireframe of Viewing Perspective in the Experiment Scene.

4.5.5 Jet-force Mobile

This section describes the system setup of the Jet-force mobile application along with its interaction design.

System Setup

The Jet-force mobile application is done by deploying the built project to Android-based mobile devices. Two SDK packages, namely, the Java JDK and the Android SDK Tools, are required to compile the project to an executable .apk file that can be installed and run on any compatible Android-based devices. Fig. 22 shows the diagram of deployment to Android-based mobile devices.

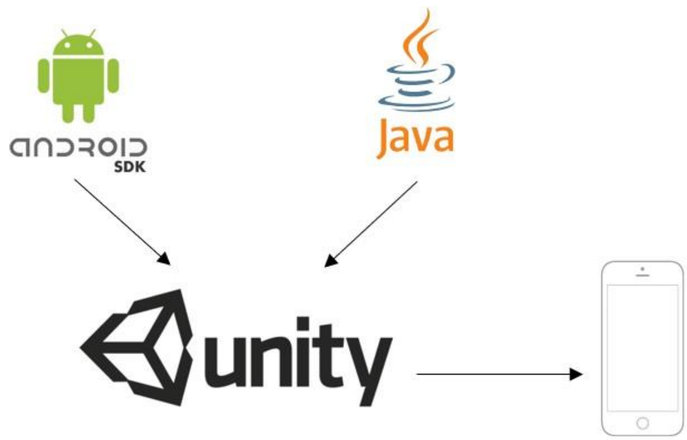


Fig. 22. Deployment to Android-based Mobile Devices.

The hardware to power the virtual experiment is a 10-inch Samsung Galaxy multi-touch tablet running on Android OS version 5.0. Fig. 23 illustrates the mobile device setup of the virtual Jet-force experiment application.

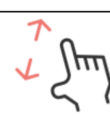
Fig. 23. Mobile Device Setup.

Interaction Design

Most touchscreen-based mobile devices support tracking up to five fingers simultaneously (multi-touch). The interaction design of the Jet-force experiment mobile application follows the standard gesture control mechanism for touch screens as shown in TABLE 12. The tap gesture corresponds to the selection command while the spread/pinch gesture corresponds to zooming in/out commands. The pan gesture is not implemented since the application supports "teleport" features of five different preset camera views.

TABLE 12

TOUCH SCREEN GESTURE

	
Tap (Select)	Spread/Pinch (Zoom)

4.5.6 Jet-force PC

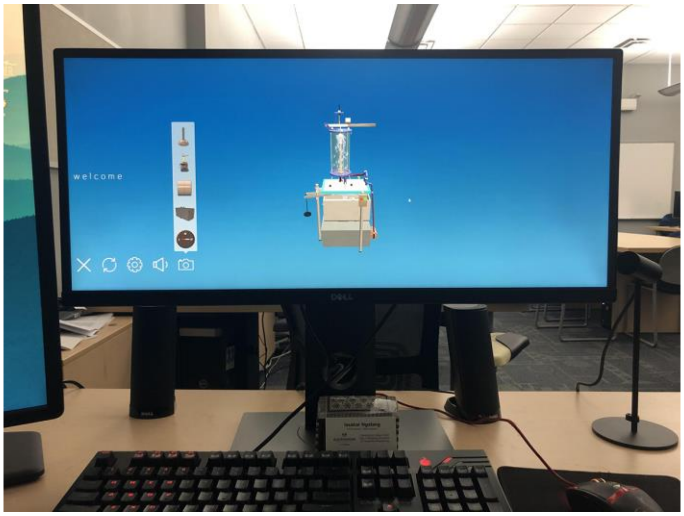
This section describes the system setup of the Jet-force PC application along with its interaction design.

System Setup

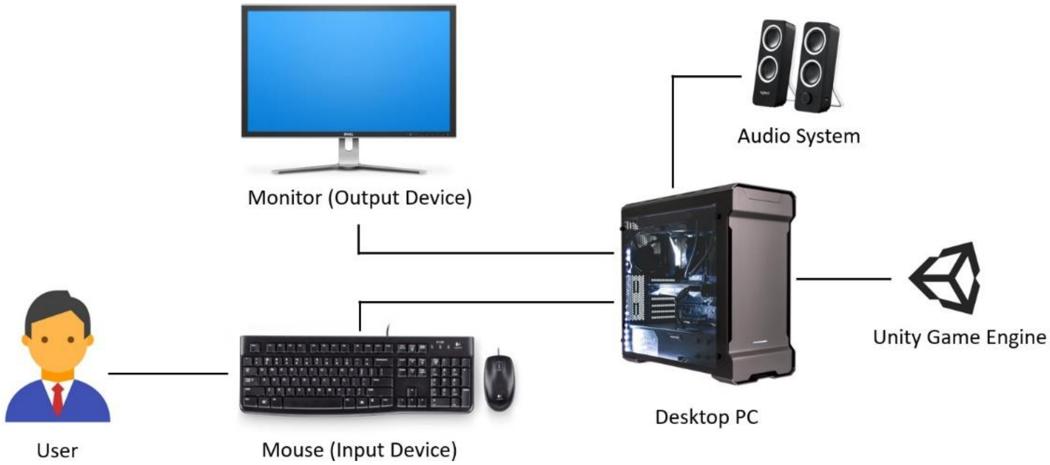
To deploy the Jet-force application to a Windows PC, no SDK packages are required. The project files are compiled to a standalone .exe file that can be run directly on a Windows PC with 32-bit and 64-bit operating system. Fig. 24 describes the deployment diagram.

Fig. 24. Deployment to Windows Desktop PC.

The hardware includes a 21:9 aspect ratio 32-inch widescreen monitor as the display, a pair of keyboard and mouse as the input device, a pair of the USB speakers as the audio system, and an Intel-based desktop PC with 64-bit of Windows 10 Education Version. Fig. 25 shows the desktop PC setup of the virtual Jet-force experiment application.



(a)



(b)

Fig. 25. Desktop PC Setup: (a) Hardware Setup, (b) Setup Component Illustration.

Interaction Design

The interaction of the desktop PC version of the Jet-force experiment application is done using a computer mouse, which offers a virtual 2D cursor for pointing in the virtual environment and a left-mouse mouse button to click for selection. Fig. 26 show a 2D illustration of a computer mouse interaction.

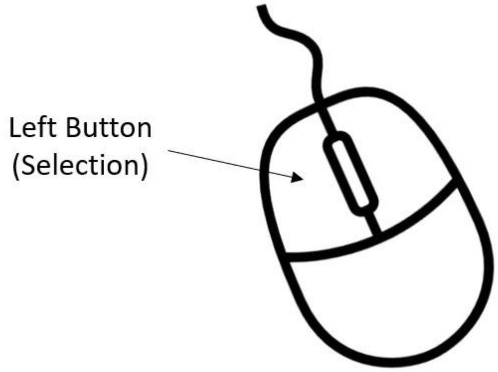


Fig. 26. Mouse Interaction.

4.5.7 Jet-force Z-Space

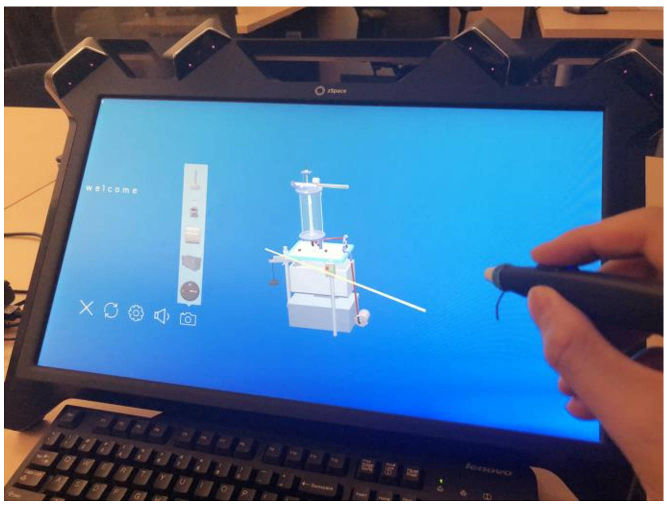
This section describes the system setup of the Jet-force Z-Space application along with its interaction design.

System Setup

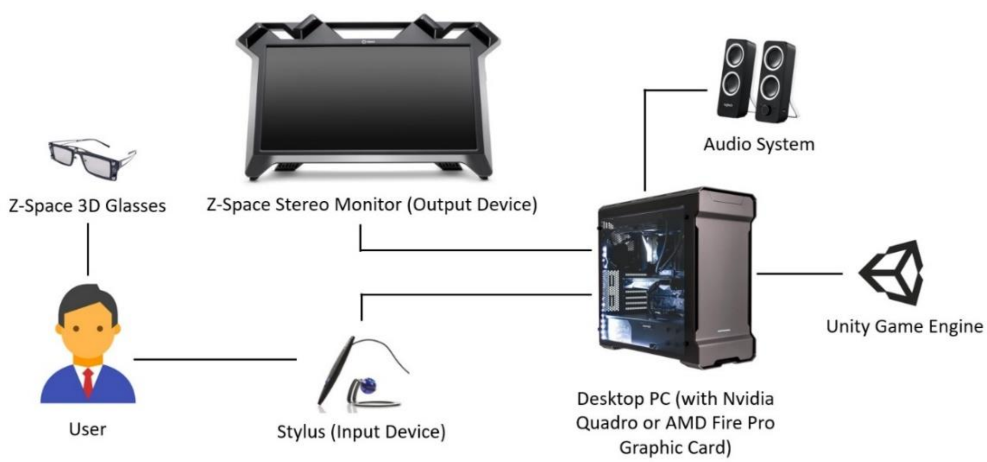
Z-Space has its own plugin for Unity called the "Z-Core". This plugin, packed as a Unity assets package, can be directly imported to Unity game engine. This package provides developers with all the necessary APIs for accessing the stereo display and stylus. Fig. 27 illustrates the deployment diagram for the Z-Space tablet.

Fig. 27. Deployment to the Z-Space Tablet.

The hardware setup includes a Z-Space device featuring four infrared (IR) sensors and a 3D stereoscopic display. A pair of 3D trackable glasses are also included in this setup. The Z-Space of this version is not a standalone system, meaning that it must run alongside with a desktop PC with a professional graphics card such as Nvidia Quadro or AMD FirePro GPUs to run in quad buffer mode for the stereo display. Fig. 28 shows the Z-Space setup of the virtual Jet-force experiment application.



(a)



(b)

Fig. 28. Z-Space Tablet Setup: (a) Hardware Setup, (b) Setup Component Illustration.

Interaction Design

The Z-Space stylus serves as the interaction/input device for the Z-Space system. It supports 6 degree-of-freedom (DoF) movement and is also trackable by the IR sensors embedded on top of the Z-Space display screen. The stylus supports a ray-casting/virtual laser beam for object selections in virtual environments. As the ray intersects with a virtual object, the primary button can be pressed to confirm the selection. Fig. 29 describes a 2D illustration of the Z-Space stylus interaction.

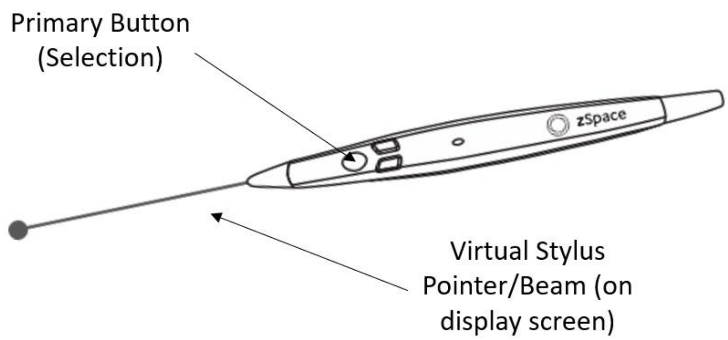


Fig. 29. Z-Space Stylus Interaction.

4.5.8 Jet-force VR

This section describes the system setup of the Jet-force VR application along with its interaction design.

System Setup

Virtual Reality Toolkit (VRTK) is a third-party plugin providing VR solutions in Unity. The plugin can be downloaded directly from the Unity asset store and then imported to the Unity game engine. VRTK supports both SteamVR and Oculus SDK. With the help of VRTK plugin, developers can quickly learn and use some of the pre-built functions that may speed up the creation process. The finished project can be easily deployed on HTC Vive or the Oculus headset. Fig. 30 illustrates the deployment diagram for the VR headset (HTC Vive or Oculus Rift).

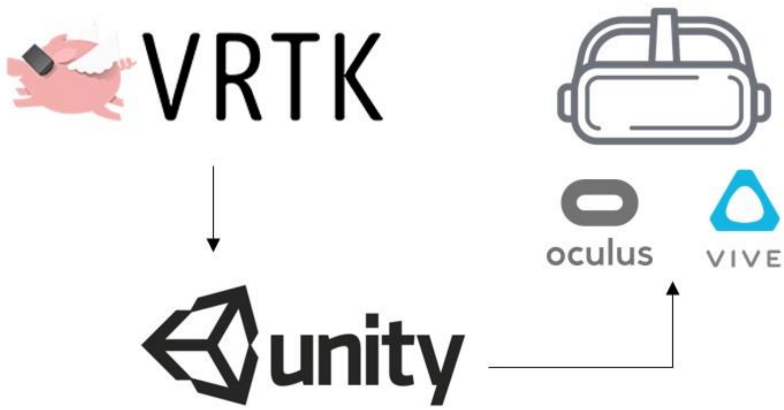
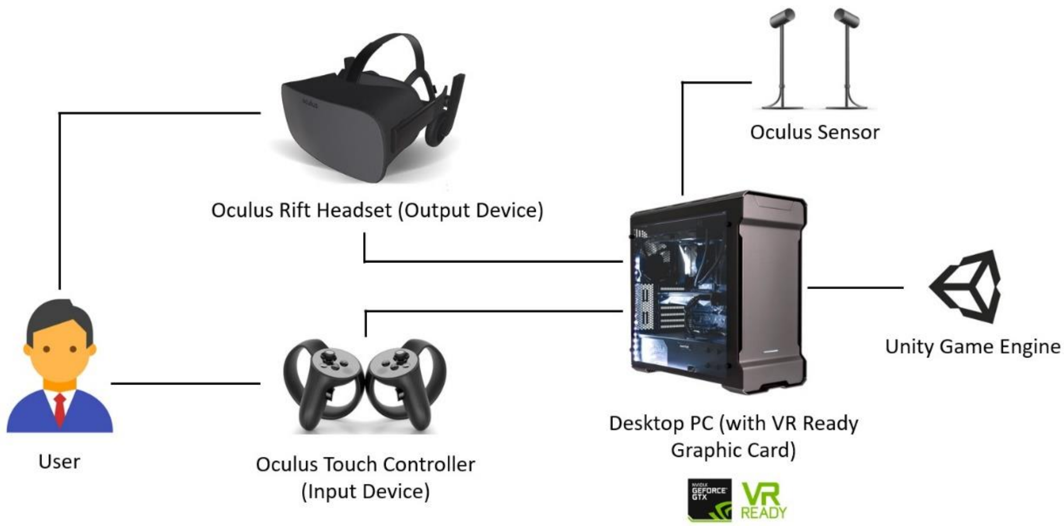


Fig. 30. Deployment to VR Headsets.

The hardware setup includes the Oculus Headset with OLED panel for each eye, a pair of trackable Oculus Touch controller with 6 DoF, a pair of positional trackers for tracking a player's sitting position. The computer must have a VR ready Nvidia or AMD Radeon graphics card to run the VR Headset. Fig. 31 shows the VR headset (Oculus) setup of the virtual Jet-force experiment application.

(a)



(b)

Fig. 31. VR Headset Setup: (a) Hardware Setup, (b) Setup Component Illustration.

Interaction Design

The Oculus headset tracks the Oculus Touch controller driven by users' hand position and movement. The virtual representation of a 3D hand avatar or a 3D Oculus Touch controller avatar appears in the virtual scene. A pointer or a ray-casting beam can also be toggled in the virtual scene for selecting virtual objects. Fig. 32 illustrates the 3D hand avatar with ray-casting enabled in the virtual environment. When the ray-casting beam intersects with the interactable object, the beam color will turn red. Otherwise, the beam color stays green. This feature is included in the VRTK unity plugin.

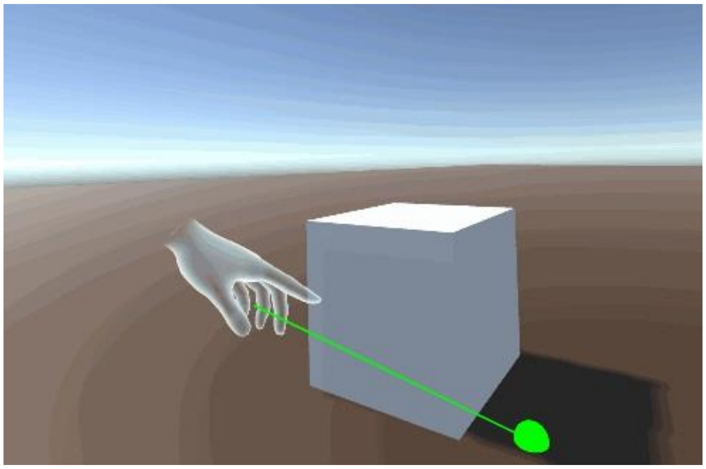


Fig. 32. Oculus Touch Virtual Hand Avatar Pointer.

To take full advantages of a pair of Oculus Touch controllers with a tracking and ray-casting feature as well as thumbstick for navigation, the 2D UI menu was eliminated in the VR version of the Jet-force experiment application. Instead, a 3D virtual laboratory environment is added to enhance the realism of the laboratory environment. A user needs to manually navigate to different areas of the virtual laboratory environment to work on a specific task by using the thumbstick on the left controller. When toggling the ray-casting beam by pressing the thumbstick on the right controller, selections can be made by pointing a laser-beam to the selected object and pressing the right trigger button. Fig. 33 describes an illustration of the Oculus Touch Controller interaction.

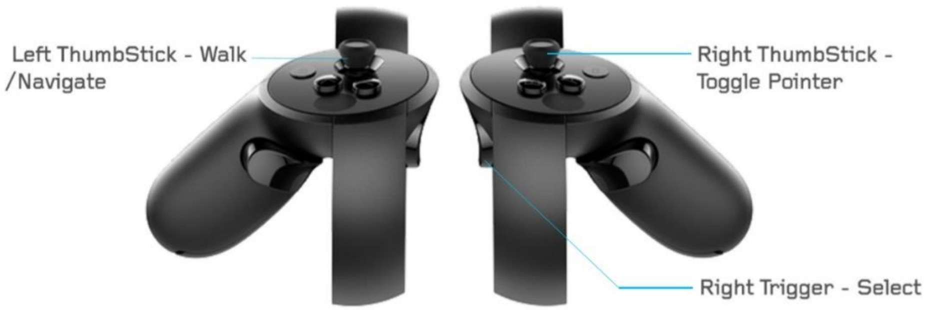


Fig. 33. Oculus Touch Controller Interaction.

4.5.9 Jet-force CAVE

This section describes the system setup of the Jet-force experiment CAVE application along with its interaction design.

System Setup

MiddleVR is a plugin and library that handles multiple VR solutions, and it is made especially convenient to work with a multi-wall projection screen CAVE. MiddleVR offers an interface that will create a bridge, which is based both on the MiddleVR API and the host game engine API (in this case Unity). Fig. 34 describes the deployment diagram for the CAVE. Configuration files, which may include cameras, viewports, or 3D notes, can be created and saved in the MiddleVR configurator. After directly importing the MiddleVR package in Unity, the user can load the configuration file generated by the MiddleVR configurator.

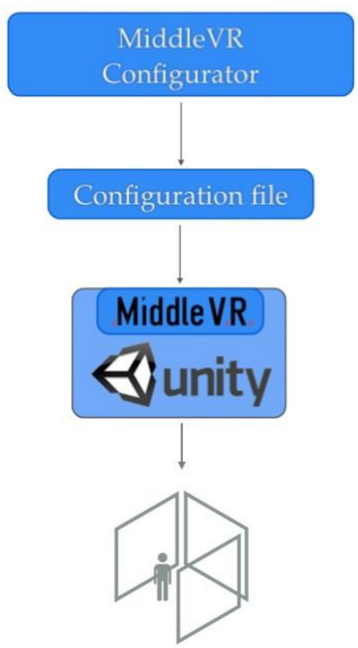
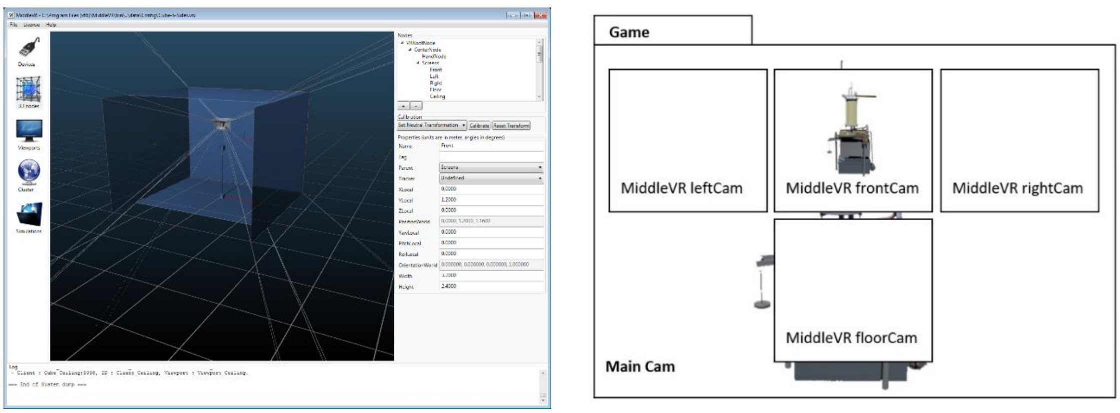


Fig. 34. Deployment to the CAVE.

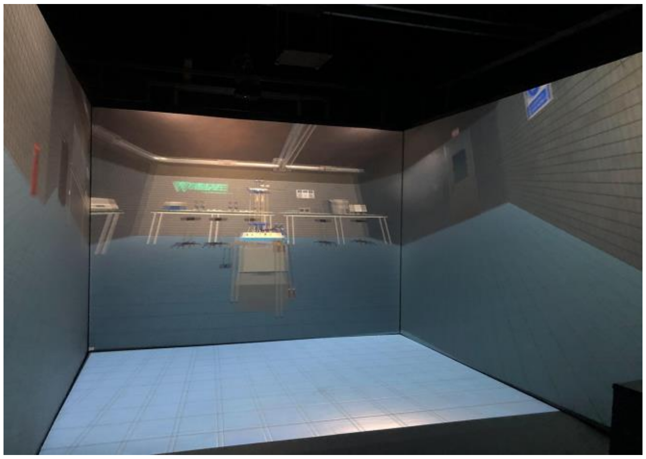
There is a predefined configuration file “Cube-5-Sides-Flatten” consisting of multiple stereoscopic walls in MiddleVR configurator, which offers an intuitive way for setting up the screen projections in the CAVE, as shown in Fig. 35 (a). Once the configuration file is modified and saved, it can be imported to Unity. The MiddleVR camera in the configuration file will override the Unity in-game camera, as shown in Fig. 35 (b), to map the whole environment into different projection screens of the CAVE.



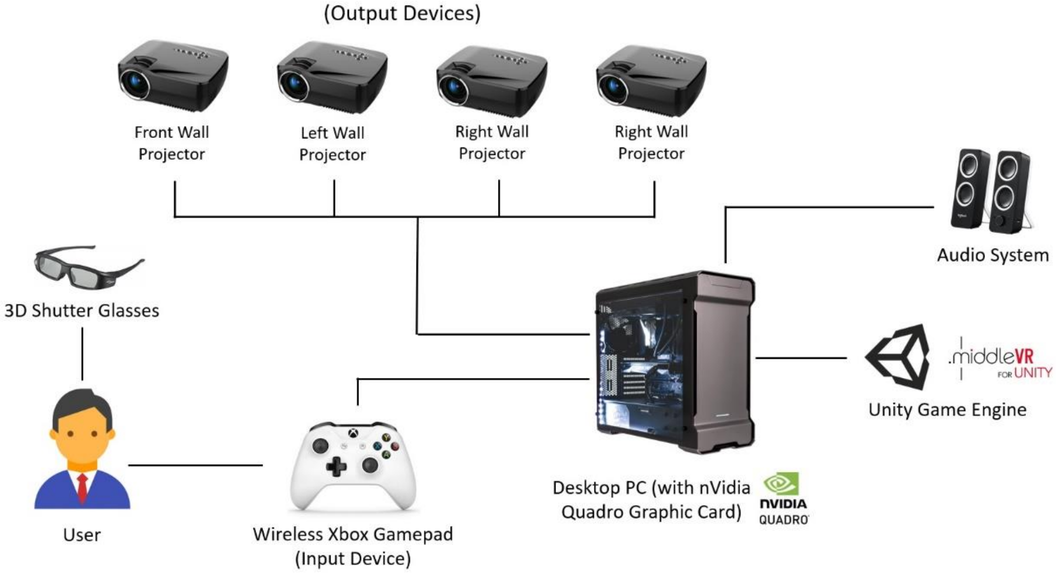
(a) (b)

Fig. 35. MiddleVR Configuration for the CAVE: (a) CAVE Configurator Setup, (b) MiddleVR Camera for the CAVE.

The hardware setup includes four 3D projectors with each set to 1024 x 768 resolution with screen refresh rate of 120Hz, a pair of battery powered 3D shutter glasses, an Xbox gamepad as the input device, and a desktop computer equipped with a Nvidia Quadra graphics card that has four video outputs for connecting all four 3D projectors. Fig. 36 shows the CAVE setup of the virtual Jet-force experiment application.



(a)



(b)

Fig. 36. CAVE Setup: (a) Hardware Setup, (b) Setup Component Illustration.

Interaction Design

The interaction of the CAVE version of the Jet-force experiment application is done using a wireless Xbox Gamepad. Each button is mapped into a specific action such as cycling camera views, powering on the equipment, loading the weight, etc. Fig. 37 describes an illustration of the gamepad button mapping for the CAVE environment.

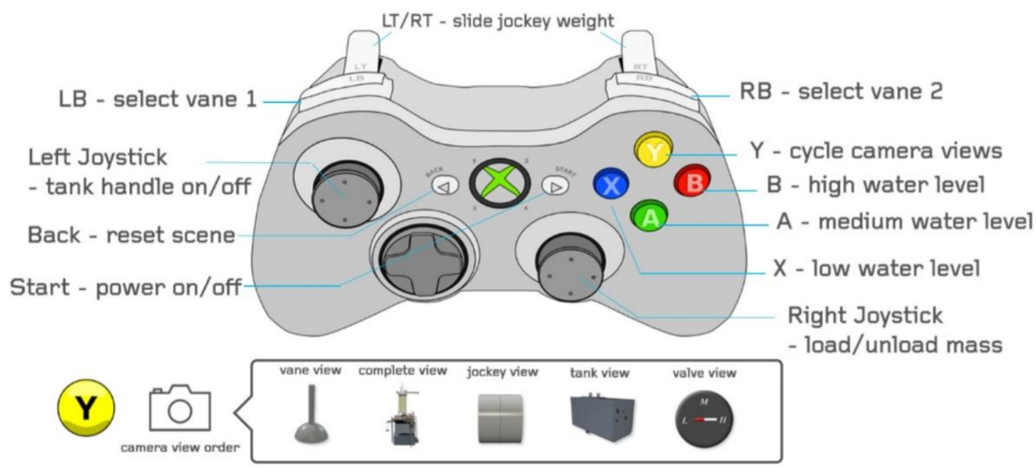


Fig. 37. CAVE Xbox Gamepad Interaction.

CHAPTER 5

RESULTS

This research study involves collecting user data to validate the usability and effectiveness of a 3D educational virtual laboratory on five virtual reality (VR) platforms/devices (a mobile tablet, a desktop PC, a 3D stereo tablet (Z-Space), a VR headset (Oculus Rift), and the CAVE). The reason for conducting this study is to investigate and compare which VR device will provide an overall best fit for the 3D educational content that we designed regarding the interaction level, usability and performance effectiveness. ***The research study is approved by the Institutional Review Board (IRB) with reference number: 18-068***.

5.1 Participants Demographics

A total of 30 subjects (17 males and 13 females) participated in this study over a three-month timespan during summer 2018. Among these participants, the age distribution ranges from 18 years old to 66 years old with half of the population from the 18~29 age group. Regarding the education level, more than half (55%) of the participants have earned or are working on a Ph.D. degree, the rest of the population consists of participants with or working on master (10%), undergraduate (32%), and medical degree (3%). A little less than half (47%) of the population indicated that they are majoring in engineering related field while more than half (53%) had their educational background in the non-engineering related field including computer science, information technology, psychology, and liberal arts. Regarding the tech-savviness, a little less than half (44%) of the participants identified themselves as proficient technologies users. The other 53% stated that they are familiar with technologies to some degree. Regarding the immersive VR experience, only 37% of the participants had previous experience with the VR headsets or the CAVE. Fig. 38. shows the participants' demographic information in pie charts.

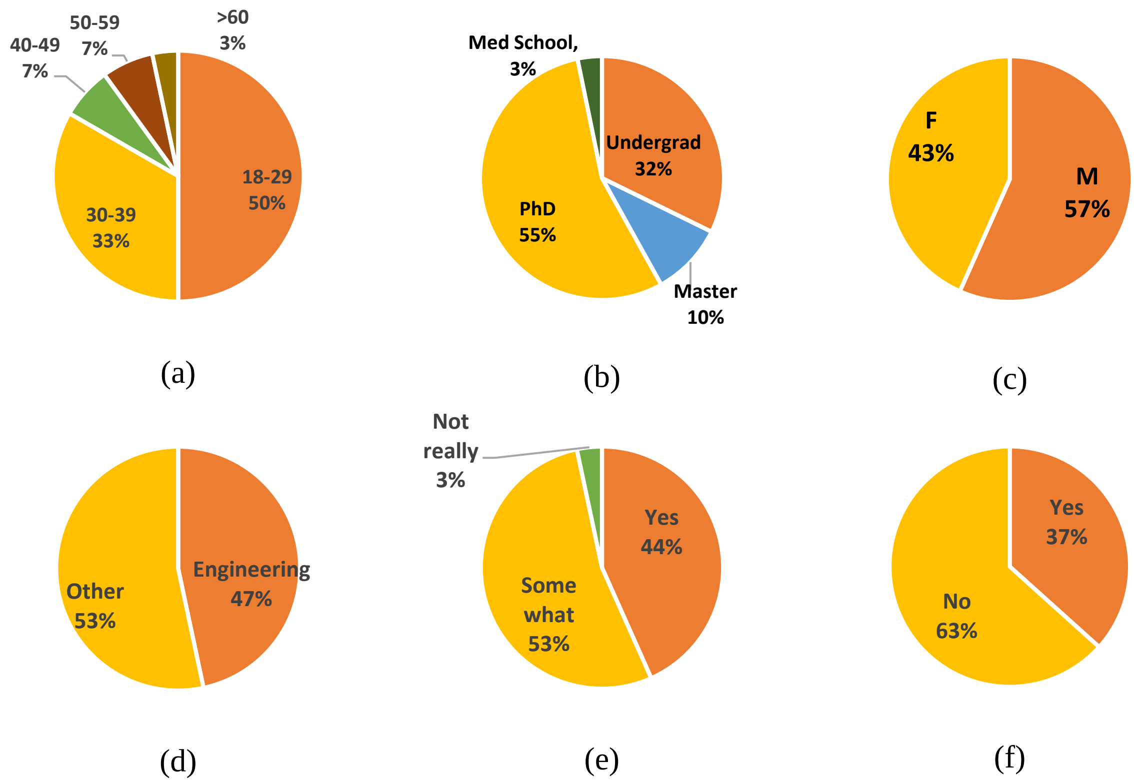


Fig. 38. Demographics of 30 Participants: (a) Age Distribution, (b) Education Level, (c) Gender Distribution, (d) Education Background, (e) Tech-savviness, (f) Previous Immersive VR Experience.

5.2 Procedure and Methods

All participants were asked to read, understand, and sign the consent form prior to the study. Then a simulator sickness pre-screening questionnaire was asked to be signed to ensure that participants are free of motion sickness. Next, participants were given a pre-interview questionnaire for collecting their demographic information as mentioned in the previous section. Afterward, participants were randomly assigned to one of the five groups (Group A – Group E).

Each group contains the experiment sequence with different VR devices. For instance, if a participant were placed in Group A, then he/she would proceed with the mobile device first, followed by the PC, Z-Space, VR headset, and CAVE. The reason for creating such groups is to minimize the bias of participants getting too familiar with the last VR device after repeating the same virtual lab experiment on the previous four devices. TABLE 13 summarizes the group order.

TABLE 13

GROUPS WITH RESPECTIVE VR DEVICE SEQUENCE

Group/Order	**1**	**2**	**3**	**4**	**5**
A	Mobile	PC	Z-Space	VR	CAVE
B	PC	Z-Space	VR	CAVE	Mobile
C	Z-Space	VR	CAVE	Mobile	PC
D	VR	CAVE	Mobile	PC	Z-Space
E	CAVE	Mobile	PC	Z-Space	VR

After the group assignment, participants were asked to perform the same virtual lab activity on five different VR systems following the order of that specific group they were assigned to. The steps are described as the following:

1. The researcher provides a briefing of the virtual lab activity procedure with the aid of an instructional manual (participants are allowed to look at the instructional manual while performing the virtual experiment)
2. The researcher prepares and starts the virtual lab activity.
3. The participant is asked to complete the virtual lab activity on one of the VR platforms (depending on the sequence of the group that the participant is assigned to).
4. Direct observation form is filled out by the researcher during the virtual lab activity.

5. The participant is asked to fill out an evaluation questionnaire at the end of the virtual lab activity.

6. The participant moves on to the next VR platform and repeats step 1 to 5 until finishing virtual lab activities on all five VR platforms.

7. The participant fills out a post-interview questionnaire at the end of the study.

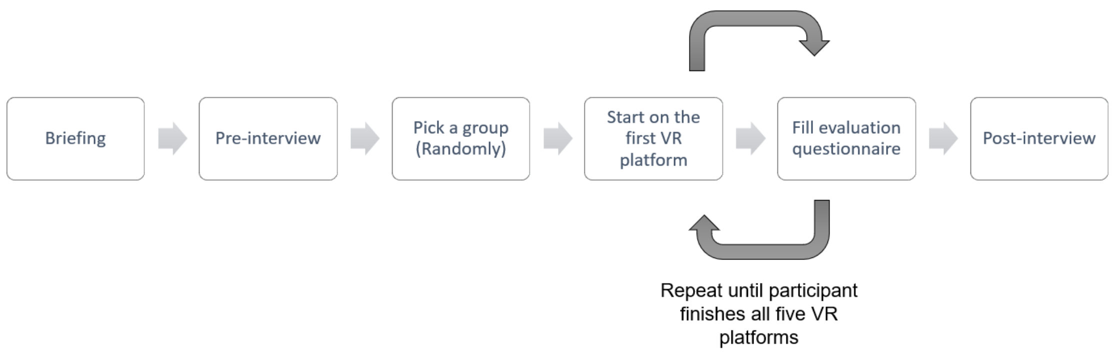


Fig. 39. Experiment Procedure Flow-chart.

Fig. 39 illustrates the flow-chart of the experimental procedure. No identifiable personal information is required or retained for this study. Participants are only asked for the last 4-digit of university identification number as a document tag to identify their responses. Since each participant will be asked to finish five questionnaire forms on five VR devices, the document tag will help to differentiate one subject's response with another (e.g., the document tag can help not to mix up subject A's response with subject B's response if they both did a questionnaire on a mobile device).

5.3 Quantitative Assessment

The quantitative assessment is based on the statistical analysis of participants' quantified questionnaire results (subjective) and direct observation data (objective). The evaluation questionnaire consisted of 21 questions in the form of a 5-point Likert Scale, with one being "*Strongly Disagree*" and five being "*Strongly Agree.*" The questionnaire covers six factors: immersion, control, concentration, usability, emotion, and comfort. Each factor is composed of a series of Likert-type items/questions that originated from different literature (illustrated in TABLE 14.). A complete table with detailed questions is described in Appendices.

TABLE 14

EVALUATION QUESTIONNAIRE TO MEASURE SIX FACTORS IN VIRTUAL ENVIRONMENTS

Questions	Category	Original Questionnaire	Source
Item 1~5	Immersion	*PQ from Witmer & Singer 1998*	*Witmer & Singer 1998* *Kronqvist et al. 2016* *Tcha-Tokey et al. 2016*
Item 6~9 Item 10~12	Control Concentration	*ITQ from Witmer & Singer 1998*	*Witmer & Singer 1998* *Kronqvist et al. 2016* *Tcha-Tokey et al. 2016*
Item 13~17	Usability	*SUS from Brooke 1996*	*Brooke 1996*
Item 18~19	Emotion	*Pekrun et al. 2011*	*Pekrun et al. 2011* *Tcha-Tokey et al. 2016*
Item 20~21	Comfort	*Verhagan 2008*	*Verhagan 2008*

The direct observation is a form that is designed based on the overall familiarity with the experimental procedure. It must be filled out by the researcher while the participant is performing the virtual experiment on each platform. Time elapsed during the experiment on each VR platform as well as the number of errors per trial will be recorded on the form by the researcher. The complete direct observation form is included in Appendices.

5.3.1 Questionnaire Results

The average score is calculated based on a series of Likert-type items/questions for each factor from 30 participants in all five VR platforms (mobile, PC, Z-Space, VR, and CAVE). The results are shown in TABLE 15 and Fig. 40.

TABLE 15

QUESTIONNAIRE RESULTS BASED ON SIX FACTORS ACROSS FIVE VR PLATFORMS

(*N = 30*)

VR Platform	**5-Point Likert Scale Mean Score**						
	Immersion	*Control*	*Concentration*	*Usability*	*Emotion*	*Comfort*	*Avg*
Mobile	3.146667*	4.125	4.177778	4.32	4.1	4.13333*	4.000463
PC	3.413333	4.258333*	4.344444*	4.38*	4.06667*	4.08333	4.091018*
Z-Space	3.88	3.708333	3.877778	3.786667	4.31667	3.61667	3.864352
VR	4.546667*	4.05	4.055556	4.106667	4.5*	3.16667*	4.070926
CAVE	3.906667	3.608333*	3.622222*	3.64*	4.05	3.61667	3.740648*

**highlights the lowest and highest value in each column*

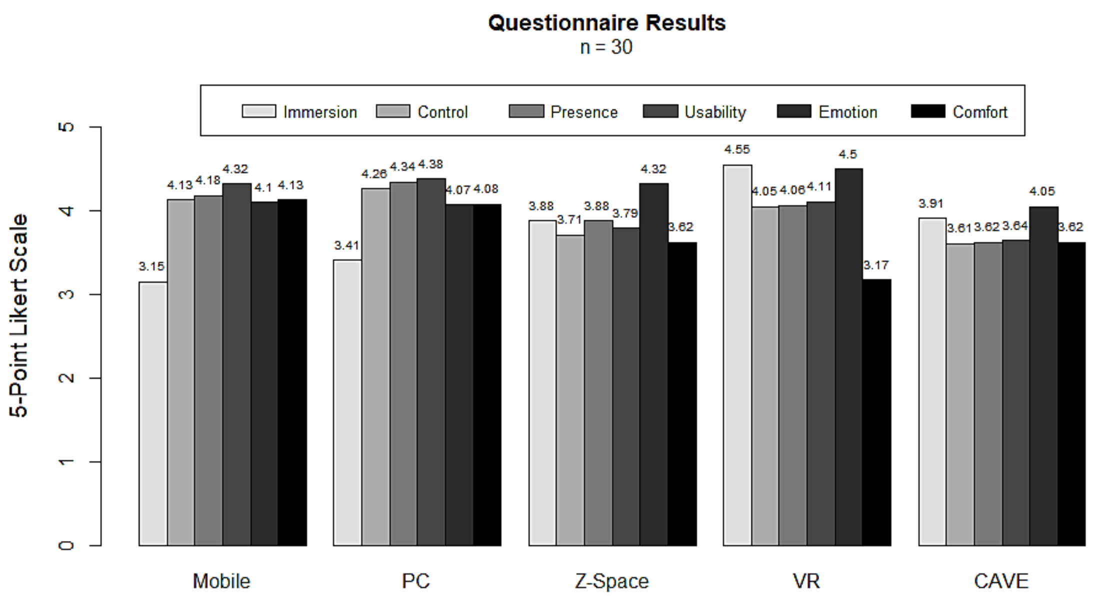


Fig. 40. Questionnaire Results based on Six Factors across Five VR Platforms (*n* = 30).

The results revealed that the full-immersive VR platforms including the Oculus Rift (VR headset) and the CAVE produced the top two highest average scores (4.55 and 3.91 respectively), taking the lead in the immersion category. Most participants believed that the mouse and the touchscreen, as their primary input control of the PC and the mobile platform, were easy to use and drew less distraction while performing the virtual laboratory experiment. Regarding the usability, the PC and the mobile platform scored the best while the CAVE platform scored the lowest. Regarding the emotion factor, most of the participants enjoyed their experience using the VR and the Z-Space platform, as these devices were relatively new and fun to play with. The mobile and the PC platform provided the best comfort while the VR headset caused minor discomfort (e.g., slight simulator sickness) for some participants.

5.3.1 Hypothesis Test on Questionnaire

A statistical hypothesis test was conducted based on the 5-point Likert scale scores from six factors across five VR platforms. A paired sample t-test was used since *(i)* two experimental conditions (e.g., PC immersion vs. VR immersion) will be compared at a time and *(ii)* the same subject took part in both experimental conditions that will be compared (e.g., participant A goes through the experiment first on the PC, then on the VR platform). This also suggests that the two sampled data are dependent on each other. Using a null hypothesis with the means of two data sets, it will be rejected if the t-test p-value is under 0.05 at the 95% confidence level. On the other hand, if the p-value is above 0.05, then the two datasets do not differ. The hypothesis test results are done in R Studio and summarized in the following tables. TABLE 16 shows the test statistics and p-value comparisons of evaluation questionnaire score based on immersion.

TABLE 16

TEST STATISTICS COMPARISONS OF EVALUATION QUESTIONNAIRE SCORE BASED ON IMMERSION AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE, α = 0.05*)

Multiple Comparison Test (Immersion)	**Mean Difference**	***P-value***
Mobile vs. PC	0.2666667	0.1045
Mobile vs. Z-Space	***0.7333333***	***9.947e-06***
Mobile vs. VR	***1.4***	***2.606e-08***
Mobile vs. CAVE	***0.76***	***3.078e-05***
PC vs. Z-Space	***0.4666667***	***0.00407***
PC vs. VR	***1.133333***	***3.638e-07***
PC vs. CAVE	***0.4933333***	***0.007787***
Z-Space vs. VR	***0.6666667***	***7.469e-05***
Z-Space vs. CAVE	0.02666667	0.8679
VR vs. CAVE	***0.64***	***0.001249***

From TABLE 16, it has been shown that significant differences were found when comparing low-immersive devices (mobile and PC) with full-immersive devices (VR headset and CAVE). The semi-immersive device Z-Space also demonstrated a higher level of immersion than all low-immersive devices. However, when comparing the Z-Space with the full immersive devices such as the VR headset and the CAVE platform, a significant difference was only found between the Z-Space and the VR headset. No difference was found between the Z-Space and the CAVE. Comparison between the low-immersive devices (mobile vs. PC) demonstrated no significant difference.

TABLE 17

TEST STATISTICS COMPARISONS OF SURVEY QUESTIONNAIRE SCORE BASED ON CONTROL AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE, α = 0.05*)

Multiple Comparison Test (Control)	Mean Difference	*P-value*
Mobile vs. PC	0.1333333	0.2768
Mobile vs. Z-Space	***0.4166667***	***0.009646***
Mobile vs. VR	0.075	0.6817
Mobile vs. CAVE	***0.5166667***	***0.00535***
PC vs. Z-Space	***0.55***	***0.0005863***
PC vs. VR	0.2083333	0.253
PC vs. CAVE	***0.65***	***0.0002391***
Z-Space vs. VR	0.3416667	0.07747
Z-Space vs. CAVE	0.1	0.5555
VR vs. CAVE	0.4416667	**0.0507**

Regarding the control factor, both the touchscreen (mobile) and the mouse (PC) outperformed the Z-Space stylus and the gamepad (CAVE), as illustrated in TABLE 17. No significant difference was found between the mouse and the touchscreen. Similarly, when comparing the Oculus Touch controller with the touch screen, the mouse, the Z-Space stylus, and the gamepad, respectively, no significant differences were found. However, it is worth mentioning that the p-value from the comparison test between the Oculus Touch and CAVE gamepad is at 0.0507. This indicates a tendency for a significant difference between the two if the sample size is increased.

TABLE 18

TEST STATISTICS COMPARISONS OF SURVEY QUESTIONNAIRE SCORE BASED ON CONCERTATION AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE*, *α = 0.05*)

Multiple Comparison Test (Concentration)	Mean Difference	*P-value*
Mobile vs. PC	0.1666667	0.261
Mobile vs. Z-Space	0.3	0.09908
Mobile vs. VR	0.1222222	0.4378
Mobile vs. CAVE	***0.5555556***	***0.0186***
PC vs. Z-Space	***0.4666667***	***0.009818***
PC vs. VR	0.2888889	0.06917
PC vs. CAVE	***0.7222222***	***7.997e-05***
Z-Space vs. VR	0.1777778	0.1838
Z-Space vs. CAVE	0.2555556	0.2186
VR vs. CAVE	***0.4333333***	***0.04185***

TABLE 18 illustrates the statistical comparison of questionnaire scores based on the level of concentration. Significant differences were found when comparing the CAVE with the mobile, the PC, and the VR, respectively, which may imply that the CAVE system caused more distractions as participants concentrated more on the input device (*i.e.*, the gamepad) than the assigned task. There was also a significant difference between the PC and the Z-Space platform as participants commented a slight latency on the stylus when performing the assigned task. Overall, participants were able to better concentrate on the assigned task on the PC and the mobile platform. The VR headset and the Z-Space had an average amount of distraction while the CAVE demonstrated the most amount of distraction.

TABLE 19

TEST STATISTICS COMPARISONS OF SURVEY QUESTIONNAIRE SCORE BASED ON USABILITY AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE*, *α = 0.05*)

Multiple Comparison Test (Usability)	**Mean Difference**	***P-value***
Mobile vs. PC	0.06	0.5832
Mobile vs. Z-Space	***0.5333333***	***0.001007***
Mobile vs. VR	0.2133333	0.2433
Mobile vs. CAVE	***0.68***	***0.002493***
PC vs. Z-Space	***0.5933333***	***0.0006782***
PC vs. VR	0.2733333	0.125
PC vs. CAVE	***0.74***	***5.235e-05***
Z-Space vs. VR	***0.32***	***0.03135***
Z-Space vs. CAVE	0.1466667	0.4115
VR vs. CAVE	***0.4666667***	***0.03523***

Regarding the system usability, low-immersive devices, such as the mobile and the PC, were generally better than the CAVE and the Z-Space. As demonstrated in Table 19, significant differences were found when comparing the mobile device with the Z-Space and the CAVE, respectively. Similarly, the PC also demonstrated significantly better usability than the Z-Space and the CAVE. In addition, the VR headset had significantly better usability than the Z-Space and the CAVE, although no significant differences were found when comparing the VR headset with the low-immersive devices (mobile and PC).

TABLE 20

TEST STATISTICS COMPARISONS OF SURVEY QUESTIONNAIRE SCORES BASED ON EMOTION AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE, α = 0.05*)

Multiple Comparison Test (Emotion)	**Mean Difference**	***P-value***
Mobile vs. PC	0.03333333	0.8012
Mobile vs. Z-Space	0.2166667	0.2356
Mobile vs. VR	0.4	0.06957
Mobile vs. CAVE	0.05	0.745
PC vs. Z-Space	0.25	0.1579
PC vs. VR	***0.4333333***	***0.04676***
PC vs. CAVE	0.0166667	0.9326
Z-Space vs. VR	0.1833333	0.2276
Z-Space vs. CAVE	0.2666667	0.154
VR vs. CAVE	***0.45***	***0.04018***

The VR headset (Oculus Rift) was at the top of the chart regarding subjects' emotions. Most participants commented that the VR headset brought more immersive and exciting experiences than other devices. However, significant differences were only found when comparing the VR headset with the PC and the CAVE platform. It is not surprising to see that full-immersive systems are generally more exciting than the low-immersive devices that we use regularly. Nevertheless, it is surprising to observe that the CAVE fell short on the emotion/excitement aspect. This is because of participants feeling the annoyance of remembering the button mapping on the gamepad.

TABLE 21

TEST STATISTICS COMPARISONS OF SURVEY QUESTIONNAIRE SCORE BASED ON COMFORT AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE*, *α = 0.05*)

Multiple Comparison Test (Comfort)	**Mean Difference**	***P-value***
Mobile vs. PC	0.05	0.5219
Mobile vs. Z-Space	***0.5166667***	***0.002278***
Mobile vs. VR	***0.9666667***	***2.789e-05***
Mobile vs. CAVE	***0.5166667***	***0.0007218***
PC vs. Z-Space	***0.4666667***	***0.003292***
PC vs. VR	***0.9166667***	***6.081e-06***
PC vs. CAVE	***0.4666667***	***0.004943***
Z-Space vs. VR	***0.45***	***0.03192***
Z-Space vs. CAVE	0	1
VR vs. CAVE	***0.45***	***0.04761***

TABLE 21 shows that the low-immersive platforms (mobile and PC) are significantly better than the semi-immersive (Z-Space) and full-immersive platforms (VR headset and CAVE) regarding the comfort factor. Participants commented that although the VR headset was more engaging than any other platforms, it caused minor simulator sickness and discomfort during the experiment. No significant difference was found when comparing the mobile and the PC. Z-Space and the CAVE provided equally comfortable experiences since the mean difference between those two devices is zero.

5.3.2 Direct Observation Results

Direct observation was designed to investigate subjects' overall familiarity with the assigned task procedure in the virtual experiment across different VR platforms. Two factors, including the time-elapsed and the number of errors per trial, will be observed. TABLE 22 shows the direct observation of task completion time across five VR platforms with a sample size of 30 subjects (with six subjects in each VR platform group). The researcher individually recorded each experiment with the time-elapsed using a stopwatch. Participants took the least average time (48.72s) to complete the virtual laboratory tasks using the PC platform, followed by the mobile (55.79s) and the Z-Space platform (57.37s). In contrast, the full immersive virtual platform including the VR (73.12s) and the CAVE (63.61s) reflected longer average completion time.

TABLE 22

DIRECT OBSERVATION OF TASK COMPLETION TIME ACROSS FIVE VR DEVICES

(*N = 30*)

VR Platform	**Interaction Device**	**Average Task Completion Time (s)**
Mobile	*Touchscreen*	55.79
PC	*Mouse*	48.72633333
Z-Space	*Stylus (Ray cast)*	57.37
VR	*Oculus controller (Ray cast)*	73.12333333
CAVE	*Gamepad*	63.60766667

Fig. 41 illustrates the average task completion across five VR devices in a box plot form. These results showed that low- and semi-immersive platforms with basic interaction devices generally took less completion time than the full-immersive platforms. Participants took the longest time to complete the laboratory tasks using the Oculus Rift (VR headset) because of extra time spent on navigation. The CAVE group took the second longest completion time because participants generally needed more time to get familiar with the gamepad control. TABLE 22 illustrates the statistical comparison of the direct observation task completion time. As expected, significant differences were found in every comparison scenario among all the VR platforms except when comparing the Z-Space with the mobile and the CAVE, respectively.

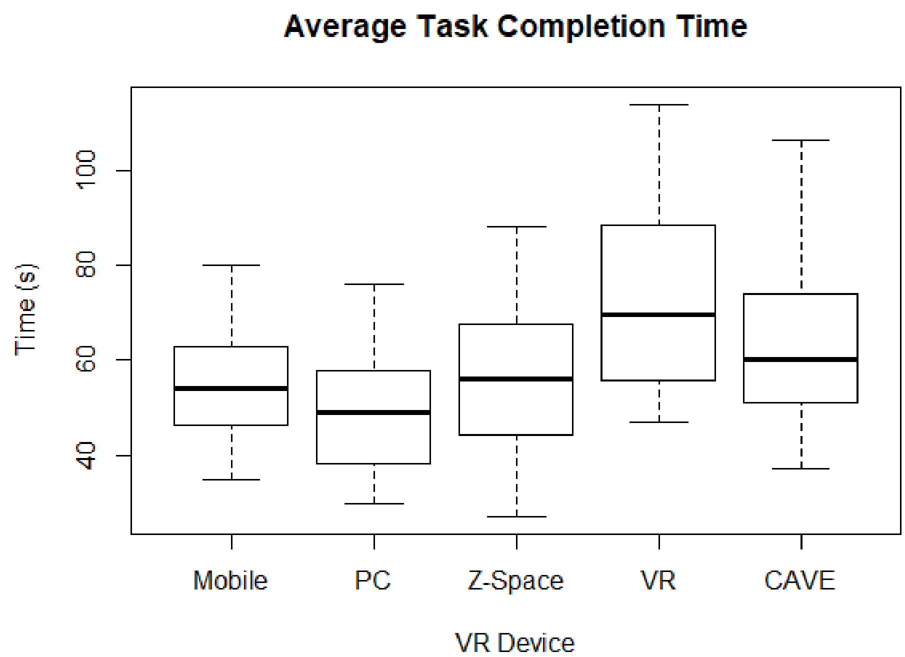


Fig. 41. Comparison of Average Task Completion Time among VR Devices.

TABLE 23

TEST STATISTICS COMPARISONS OF DIRECT OBSERVATION TASK COMPLETION TIME AMONG VR DEVICES (PAIRED T-TEST, *P-VALUE*, *α = 0.05*)

Multiple Comparison Test	Mean Difference	*P-value*
Mobile vs. PC	***7.063667***	***0.009376***
Mobile vs. Z-Space	1.58	0.643
Mobile vs. VR	***17.33333***	***3.792e-05***
Mobile vs. CAVE	***7.817667***	***0.03596***
PC vs. Z-Space	***8.643667***	***0.01072***
PC vs. VR	***24.397***	***4.999e-06***
PC vs. CAVE	***14.88133***	***0.000264***
Z-Space vs. VR	***15.75333***	***0.0002132***
Z-Space vs. CAVE	6.237667	0.06036
VR vs. CAVE	***9.515667***	***0.01317***

Fig. 42 shows the average number of errors per experiment from 30 participants across all five VR platforms (mobile, PC, Z-Space, VR, and CAVE). The researcher recorded errors if participants made procedural or technical mistakes in the assigned tasks during the experiment. The results demonstrate that the PC platform made the least average number of errors (0.73) while the CAVE platform made the most average number of errors (1.3) per experiment. However, the average number of errors in the mobile, PC, and the Z-Space group are very close to each other (0.73, 0.67, and 0.7 respectively), and are generally lower than the VR and the CAVE platform (0.93 and 1.3 respectively). Overall, the outcomes were satisfactory. Although the CAVE platform produced more errors among all the other VR platforms, an average of 1.3 errors per experiment is still considered as a satisfying performance.

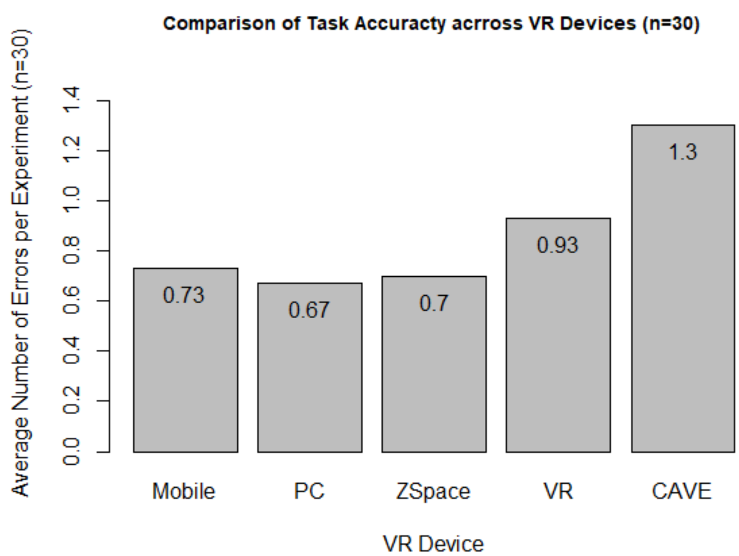


Fig. 42. Comparison of Average Task Accuracy among VR Devices.

Another comparison is made to investigate if the group order sequence made a significant impact on average task completion time. For example, the sequence of performing the virtual experiment on mobile devices is arranged with the following sequence order: Group A started mobile device first, Group E 2nd, Group D 3rd, Group C 4th, and Group B 5th. One question that needs to be addressed is that, will repetition of the experiment radically shorten the amount of time to complete the task in the virtual experiment? For example, does that mean Group A spent longer time on completing the task because they started with the mobile device first while Group B spent shorter time since they were the last one to try the experiment on a mobile device? TABLE 24 summarizes the data based on the sequence of each group starting the virtual experiment on a specific device. By looking at the table, it is observed that the order implies a general trend that the first starting device was where participants struggle the most. As participants moved forward to the last device, the average task completion time was generally shortened. The mobile and the PC device demonstrate a more consistent trend. However, the VR and the CAVE device show inconsistency as their standard deviations are also much higher.

TABLE 24

AVERAGE TASK COMPLETION TIME (BASED ON ORDER)

	Order	**1**	**2**	**3**	**4**	**5**
Mobile	Group	A	E	D	C	B
	Completion Time (sec)	63.133	55.683	56.017	50.4	53.717
	SD (σ)	11.709	8.302	6.454	6.081	10.103
PC	Group	B	A	E	D	C
	Completion Time (sec)	60.767	54.217	45.6	42.417	40.632
	SD (σ)	10.266	9.263	9.009	9.184	6.768
Z-Space	Group	C	B	A	E	D
	Completion Time (sec)	60.733	69.383	50.683	47.2	58.85
	SD (σ)	9.021	8.602	14.884	15.232	16.397

TABLE 25 (CONTINUED)

AVERAGE TASK COMPLETION TIME (BASED ON ORDER)

VR	Group	D	C	B	A	E
	Completion Time (sec)	73.217	79.117	81.367	63.267	68.65
	SD (σ)	22.978	22.550	23.099	17.021	19.418
CAVE	Group	E	D	C	B	A
	Completion Time (sec)	71.283	64.6	58.817	72.433	50.905
	SD (σ)	17.027	20.056	18.428	14.442	18.191

5.4 Qualitative Assessment

The qualitative assessment is based on the post-interview questions and discussions regarding participants' overall interactive experiences on all five platforms. The intention is to get users' subjective opinions on how they perceive and evaluate their experiences and what aspects of the study can be further improved. A few of these interview questions were based on thesis work.

What appealed to you the most in this simulation you just did?

Answers for this question vary across different aspects. Regarding the user experience on a specific device, most of the participants commented that the virtual lab on Oculus Rift was a realistic, fascinating and immersive experience as they felt a part of the environment and were able to navigate and explore the environment. Most of the participants also mentioned that it was their first time using the Oculus Rift, and thus the fresh experience played a significant role in attracting their attention. Regarding the interaction and visual design, participants commented that the interaction seemed natural and the user interface was intuitive and user-friendly. In addition, they have mentioned that the virtual lab system was relatively consistent across the different input methods and that the system was easy to learn and understand what the goal of the experiment was.

What was the thing that appealed to you the least?

Most participants commented on the interaction aspect of this question. They mentioned that there was nothing particularly exciting or glamorous about the PC or the mobile device as most participants use these devices quite frequently and are comfortable with the interaction. They also stated that the button approach on the gamepad for the CAVE was not very intuitive; the challenge was more figuring out the buttons than the actual tasks. The extra time required to learn how to use the gamepad could have distracted from the virtual experiment. A few participants felt the interaction on the Z-Space stylus was a bit clumsy as the virtual pointer was not aligned with the object they held in their hands. Some participants also brought up that the sound and water animation could be improved.

Which VR device would you say is most suited for this virtual lab? And why?

This question is intended to investigate what particular VR device the participants were in favor of based on their experiences across all five VR devices. The interview results showed that 13 participants (43.3%) were in favor of the Oculus Rift because of its high level of immersion helped them to focus on the task and eliminate any distractions in their surroundings. Six participants (20%) believed the PC is the most suitable platform for the virtual lab since PC is most comfortable and the easiest to use. For the level of complexity of tasks in the virtual lab, these participants agreed that the PC platform was more than adequate. Five participants (16.7%)

favored the CAVE as the suited platform for the virtual lab experiment because it can provide the best spatial sense for the operation. A few of them also commented that although working in the CAVE was an enjoyable experience, using the gamepad for interaction was also stressful. Three participants (10%) favored the mobile device because they believed that it was easy to control and time-saving as they were already familiar with using the device. Three participants (10%) thought that the Z-Space is the most suited platform because they enjoyed the stylus interaction along with the virtual holographic display.

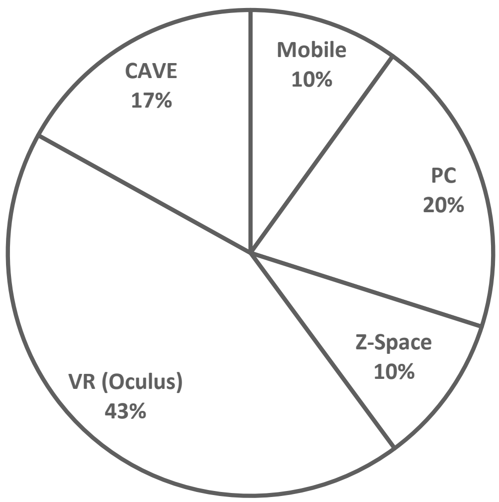


Fig. 43. Participants' Choice on the Most Suited VR Platform for Virtual Lab Experiment.

Which input device offered you the best interactive experience for this virtual lab? And Why?

This question is intended to examine which specific interaction device (among the ones that were experienced by the participants) is best suited for the current virtual laboratory experiment from the user standpoint. The interview results showed that the Oculus Touch controller was preferred by most of the participants (46.7%) because they commented that the Touch controller felt realistic and was able to track their hand and body movements. This feedback also made the experience more interactive. The second most mentioned interaction device was the mouse (23.3%). Participants believed that the mouse offered the best interactivity since it was more straightforward with click to interact. Five participants (16.7%) were in favor of the Z-Space stylus because they could navigate easily and focus more on the task itself than on the input devices instead of spending much time on learning about the controller. Three participants (10.0%) were in favor of touchscreen interactions on the mobile device because they were familiar with it, and they believed that the touch screen offered quick and efficient selection and interaction. Only one participant (3.33%) preferred the gamepad interaction in the CAVE because the button approach allowed more options to manipulate the objects in the virtual environment even though it is the most complicated one.

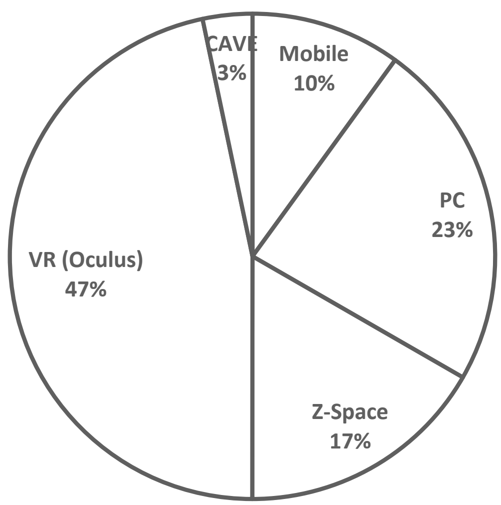


Fig. 44. Participants' Choice on the Most Suited Interaction Device.

Is there anything regarding the interactivity which you would like to see extended?

A few participants suggested that it would be helpful to incorporate motion gesture interactions in the CAVE instead of the button approach on the gamepad to take full advantages of the interaction space. Similarly, a few other participants commented using the actual hand representation in substitute of the laser beam pointer might provide a better interactive experience for the Oculus Touch controller. Other participants mentioned that the voice guide could also be added to the interaction.

CHAPTER 6

CONCLUSION AND FUTURE WORK

This work aimed to *(i)* formulate a utility framework that can assist decision-makers choosing the suited VR device matching with the design requirements along with its interaction techniques based on specific laboratory tasks, *(ii)* apply the framework with a use case, *(iii)* conduct a research study containing both the quantitative and qualitative assessment targeting on participants' general performance along with the observation of factors including interaction level, usability and performance effectiveness as a method to validate the proposed utility framework, and lastly *(iv)* analyze the quantitative and qualitative results and provide a detailed analysis to compare those key factors that may contribute to a potential increase in learning performance benefitting from different VR platforms.

From the overall results, the study demonstrated satisfying achievements. The survey questionnaire was used to investigate six unique factors (immersion, control, concentration, usability, emotion, and comfort) from participants' subjective experience when performing mechanical engineering related virtual laboratory experiment across five VR devices. The survey results reflected that the immersive VR headset (Oculus Rift) provided the highest level of immersion and brought the most substantial amount of excitement and enjoyment to participants. However, it was observed that the VR headset also prompted subtle distraction and discomfort as it was a new experience for those participants who had trouble adapting it for the first time. As one of the two fully immersive VR platforms in this study, CAVE offered a considerable amount of immersion and a spacious play area; however it fell short on control and usability since participants found more difficulty using its interaction device (gamepad) to manipulate virtual objects during specific tasks. The PC platform, on the other hand, presented the best control, concentration, and usability among all the other VR platforms from this study. The mobile platform introduced a slightly lower score than the PC platform. Nevertheless, participants rated the mobile device as the most comfortable platform as it barely caused any simulator sickness. The Z-Space in this study seemed to be a well-rounded platform for the Jet-force virtual laboratory regarding the six observed factors. It is also worth mentioning that there was no significant difference between the mobile and the PC platform average mean scores across all six factors. This may imply that participants were already familiar with operating both mobile device and PC on their daily basis, and thus the performance overall on both devices were similar.

Similar results were demonstrated in the direct observation data, where full immersive VR platforms, including the Oculus Rift (VR headset) and the CAVE, reflected longer average completion time and higher average error rate than low- and semi-immersive VR platforms. The reasons are twofold. First, navigation feature was implemented on the Oculus Rift platform instead of the teleportation feature on other VR platforms because the Oculus Rift is superior in navigation with head tracking and the Oculus Touch controller. Thus, extra time was spent on virtual navigation since participants had to virtually walk around in the 3D environment to perform various laboratory tasks accordingly using the Oculus controller Second, regarding the CAVE platform, most participants had difficulty using the button approach on the gamepad, which might lead to some distraction and potentially delayed their completion time of the virtual experiment. On the other hand, it was observed that participants could quickly adapt basic interaction devices such as the mouse and the touchscreen, and thus, the PC and mobile platform outperformed the VR headset and the CAVE regarding the average completion time. This also implied that previous experience and familiarity with these basic interaction devices could help contribute to faster completion time. The Z-Space platform again fell into the mid-range, as its average completion time is slightly higher than the PC and the mobile platform but lower than the VR headset and the CAVE platform. However, no significant differences were found when comparing the average completion time among the Z-Space, the mobile, and the CAVE platform.

For future work, the scoring scheme of the utility framework will be enhanced using machine learning techniques to increase the robustness of the recommendation system. The properties of each VR device are the feature-vectors in the training dataset to learn a model that gives recommendations based on the matching level. The weight for each factor is obtained through the optimization in the training process, reflecting the real situation for different scenarios. As a result, the weighting system can become more sophisticated and statistically reliable. Furthermore, the system will predict the most suitable VR device by giving the probability distribution for each device in the descending order. Consequently, the recommendation system will provide not only qualitative but also quantitative results so that the user can have more information in comparisons.

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APPENDICES

APPENDIX A: SIMULATOR SICKNESS PRE-SCREENING QUESTIONNAIRE

ID (last 4 digits of UIN): Date:
Gender:
Age:

This study will require you to play a simple virtual laboratory game using five virtual reality devices (e.g., Oculus Rift, PC, Z-space Tablet, Mobile and CAVE). You may face a risk of having a slight discomfort or nausea but no more than you would when playing a video game, as this study does not involve any sort of vehicular motion. To help identify people who might be prone to this feeling, we would like to ask the following questions:

Do you or have you had a history of migraine headaches? (circle one: Yes | No)
If yes, please describe:

Do you or have you had a history of claustrophobia? (circle one: Yes | No)
If yes, please describe:

Do you or have you had a history of motion sickness? (circle one: Yes | No)
If yes, please describe:

APPENDIX B: PRE-INTERVIEW QUESTIONS

ID (last 4 digits of UIN): Date:
Gender:
Age:

What is your academic level? (e.g. Undergraduate, Master, PhD, Post-Doc)

What do you currently study/What is your academic background?

Do you consider yourself as a tech-savvy person?

Do you play video games? (circle one: Yes! | No)
If so, what input device do you frequently use for playing your game? ____________________
Approximately how many hours do you spend on video games per week? (circle one: below 2 hours, 2-7 hours, 7-15 hours, 15-30 hours, above 30 hours)

Do you have previous experience with any VR devices? If so, what specific VR device? And how many months/years of experience?

APPENDIX C: EVALUATION QUESTIONNAIRE

Mobile | PC | Z-Space | VR | CAVE

ID (last 4 digits of UIN): Date:
Gender:
Age:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Immersion					
I became so involved in the virtual environment that I was not aware of the things happening around me	○	○	○	○	○
I could inspect the objects in the virtual environment	○	○	○	○	○
The visual elements of the virtual environment felt natural	○	○	○	○	○
I felt physically fit in the virtual environment	○	○	○	○	○
I became so involved in the virtual environment that I lost all track of time	○	○	○	○	○
Control					
I felt the virtual environment reacted to my actions	○	○	○	○	○
I could anticipate the results of my actions	○	○	○	○	○
The control of the input device seemed natural in the virtual environment	○	○	○	○	○
I could easily move or manipulate objects in the virtual environment with the given input device	○	○	○	○	○
Control/Presence					
I was able to examine objects closely	○	○	○	○	○
I could concentrate on the assigned tasks rather than on the input devices (e.g., gamepad, keyboard, etc.)	○	○	○	○	○

I felt proficient in interacting with the virtual environment by the end of the experience	○	○	○	○	○

	Strongly Disagree	***Disagree***	***Neutral***	***Agree***	***Strongly Agree***
Usability					
I think that I would like to use this system frequently	○	○	○	○	○
I thought the system was easy to use	○	○	○	○	○
I felt very confident using the system	○	○	○	○	○
I found that the various functions in this system were well integrated	○	○	○	○	○
I thought the system was very consistent and user-friendly	○	○	○	○	○
Emotion					
I enjoyed the challenge of learning the virtual reality interaction devices (Oculus headset, gamepad and/or keyboard)	○	○	○	○	○
I enjoyed my experience with the interaction devices (Oculus headset, gamepad and/or keyboard)	○	○	○	○	○
Comfort					
I am not feeling any major strain after using the system	○	○	○	○	○
If you are feeling strain, it is not more than using a normal computer	○	○	○	○	○

APPENDIX D: POST-INTERVIEW QUESTIONS

ID (last 4 digits of UIN): Date:
Gender:
Age:

What appealed to you the most in this simulation you just did?

And what appealed to you the least?

Which VR device would you say is most suited for this virtual lab? And why?

Which input device offered you the best interactive experience for this virtual lab? And Why?

Is there anything regarding the interactivity which you would like to see extended?

VITA

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