

## Implementation of a 3D Interactive Mobile App for Practicing Engineering Laboratory Experiment

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# **Implementation of a 3D Interactive Mobile App for Practicing Engineering Laboratory Experiment**

## **Abstract**

Performing laboratory experiment for off-campus and distance learning students is always a challenging task. Unlike other theory-based courses, engineering laboratory experiment focuses heavily on hands-on tasks. Although many web-based and other virtual reality (VR)-based laboratories widely exist, non-portability, difficult accessibility and high cost of these VR-based devices bring disadvantages to the convenience of learning. One solution is to use mobile devices, which are more portable, easier to access and cheaper in cost, and yet can still be interactive and engaging for students to practice and experience hands-on activities. In this paper, we discuss the benefits of using mobile devices for online education and the development of an Android-based 3D interactive mobile app for an undergraduate mechanical engineering laboratory. This app is capable of not only providing off-campus and distance-learning students an opportunity to practice the experiment on mobile devices, but also helping on-campus students to get familiarized with the experiment procedure prior to their physical laboratory experiment.

## 1 Introduction

Living in the 21<sup>st</sup> century, we are fortunate to have a rich amount of technologies and resources that can help us learn new skills outside the traditional classroom learning environment. As the internet continues to grow at a tremendous pace, we are able to take online classes and gain knowledge from online sources such as learning from streaming video (e.g. YouTube, lynda.com, etc.) and watching online lecture materials (e.g. MIT open course). While online education offers a variety of resources and focuses primarily on teaching the fundamental theories and concepts, one disadvantage is the lack of hands-on experience and direct interaction [1]. Particularly in engineering education, where abstract engineering concepts ideally can be better understood by doing the related hands-on activities such as laboratory experiments. To solve the issue of the practical training shortage and the lack of hands-on experience with online education, VR takes the learning experience to a next level in terms of interaction and engagement. VR refers to an artificial world that replicates the real world environment generated by computers, and that simulates the physical presence of a user in the virtual environment [2]. With the help of VR technology, we are able to not only model and simulate behaviors of physical systems or any real life scenarios in a virtual environment, but also make the virtual environment interactive by implementing it on various VR platforms or devices (e.g. a personal computer, a head-mounted device (HMD) or a mobile device). This will allow users to have direct interaction with those virtual systems and scenarios, and thus, learning can be more engaging, fun and interactive in contrast to traditional classroom or online education.

This paper presents the design of a physical-to-virtual transformation of an undergraduate mechanical engineering laboratory experiment - Jet Impact Force on Vanes (Jet-force Lab) on an Android-based mobile device using the development engine Unity 5. Section 2 reviews related literature and describes why learning on mobile device is advantageous. Section 3 provides the background information on the laboratory experiment as well as the virtual experiment we have done previously on different virtual reality (VR) platforms. Section 4 and 5 introduces the modeling software and development engine that is used for developing the mobile app as well as its development and implementation process. Section 6 discusses the benefits and the challenges of using mobile app in engineering laboratory settings. Section 7 concludes the paper and forecasts the future work.

## 2 Why Use Mobile Devices In Learning?

Many literatures indicate that VR technology has been applied to engineering education. We have demonstrated that, in our previous study, using VR devices (3D TV and the Cave Automatic Virtual Environment (CAVE)) in substitution of the traditional paper-based prelab session can outperform students' performance based on their laboratory experiment familiarity and post-quiz scores from the control group [3]. Limniou, *et al.* [4] implemented a molecular visualization chemistry module in the CAVE system. They observed that students had better understanding on molecular changes during chemical reaction when visualizing this animation in 3D on a stereoscopic display than in 2D on a traditional monitor. Shanku, *et al.* [5] introduced an interactive virtual laboratory module as a pre-lab exercise for an electrical power system engineering class. They observed that the virtual module provided students with hands-on experience and helped them better understand fundamental concepts in power systems. Amirkhani and Nahvi [6] designed an interactive virtual control laboratory (IVCL) using haptic

device for teaching engineering students control concepts. The assessment results demonstrated a satisfying outcome in students' performance, as the experimental group outperformed the control group in both the pre- and post-test.

Although successful results have been achieved with regards to students' learning performance using respective VR platforms from the literature, one common issue authors tend to ignore is whether their implementations can be widely adopted by researchers and developers with a cost-effective solution along with other factors such as portability and accessibility taken into consideration. For instance, although CAVE was a helpful visualization learning environment in the study of Limniou, *et al.* [4], the disadvantages are its high cost (it is roughly priced around \$20,000 to build a commercialized CAVE), frequent maintenance and space-consuming. In addition, while CAVE provides the capability of hosting multiple participants engaging in a virtual activity/session simultaneously comparing with many other VR platforms, any activities taken place in CAVE require participants to be physically presented on-site. Thus, CAVE is not considered as an ideal VR platform for online education, rather, it is a better environment for face-to-face collaboration. Compared with CAVE, a desktop PC seems to be a better alternative for off-campus/distance-learning students because of its relatively easy accessibility and low cost. However, one might also argue that if a desktop PC can already provide a promising solution for online education, why bother to use mobile devices? The answer is that mobile devices are much more portable, easier to access and more affordable than any of their counterparts. Table 1. shows the comparisons of a few common VR systems based on the their cost, portability and accessibility. Cost contains four levels: low, average, high and very high, with their respective ranges (low: \$0 - \$500, average: \$500 - \$1,000 and high: above \$1,000) . Portability is based on four levels: ultra-portable (*e.g.* can be carried in a pocket or a purse), portable (*e.g.* can be carried in a backpack), semi-portable (*e.g.* can be transported through cars) and none-portable. Accessibility is divided in two categories: consumer products and specialized equipment. Consumer products refer to those devices that we, as regular consumers, can purchase easily online or in store. Unlike consumer products, specialized products can be customized and ordered through vendors, which usually requires longer processing time and more complex steps to obtain. Therefore, specialized products generally have lower accessibility than consumer products.

Table 1: Comparisons of VR Systems based on Accessibility, Portability and Cost

	Cost	Portability	Accessibility	Advantages	Disadvantages
<b>Mobile VR (e.g. smartphones, tablets)</b>	Low to Average	Ultra-portable	Consumer products	Standalone system, ultra-portable, light-weight, cost-effective, high ownership	Small screen (less field of view), low-immersive
<b>Desktop VR</b>	Average to High	Semi-portable	Consumer products	Highly customizable, easy hardware upgrade, great software compatibility	Requires separate monitor, low-immersive, not portable
<b>VR Headset</b>	Average	Portable	Consumer products	Full-immersive, high level of interaction, portable (device itself)	Not standalone system, requires PC connection, can cause motion sickness
<b>CAVE</b>	Very High	None-portable	Specialized products	Full-immersive, high level of interaction, can host multiple participants for on-site collaboration	Not portable, high cost, not consumer products, requires PC connection, difficult to maintain, requires on-site usage

Table 1. indicates that mobile VR can provide more economical and portable solution than other comparative VR devices. With reference to the cost, the lower end to mid-range smartphone or mobile devices can price at anywhere between the \$50 and \$350, which are more affordable for average consumers comparing with other VR devices. In addition, mobile VR are stand-alone devices. This means that mobile VR does not rely on other devices to function. In terms of input method, build-in touchscreen on mobile devices allow users to interact with VR applications without the need of any peripherals (e.g. a stylus or a gamepad). With respect to size and weight, most mobile devices on the current market have screen sizes in diagonal ranging from 4.5 to 12 inches with weights ranging from a few ounces to 3 pounds. In regards to electronics accessibility and ownership, Pew Research Center conducted a survey and reported that 95% of American adults now own a cellphone of some kind (including 77% of smartphone owners). This is a huge leap from 35% of smartphone ownership back in 2011. In addition to smartphones, 73% of American adults now own desktop or laptop PCs, while 53% of them own tablet computers and 22% of them own e-reader devices [7].

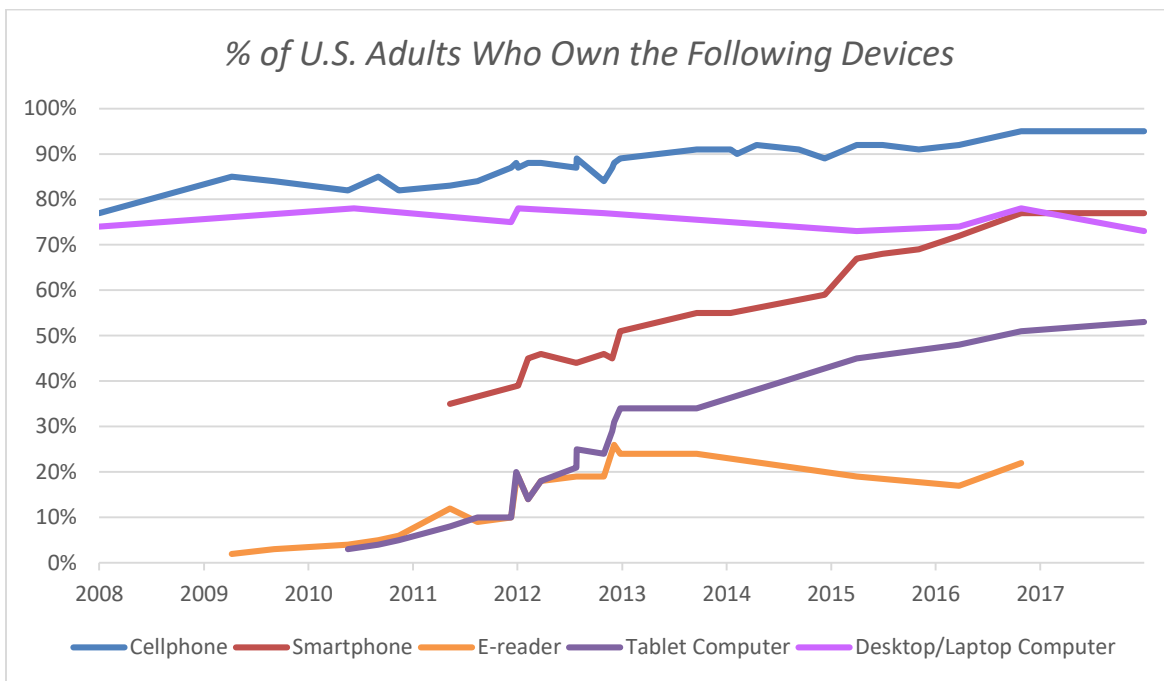


Figure 1: American Adults Personal Access to Electronic Devices [7] (Graph Reproduced from the Pew Research Center)

With reference to the learning effectiveness on mobile devices, many studies have shown that using mobile technology in education settings have positive impact on students' learning and engagement [8-16]. In particular, Kon, *et al.* [15] studied the learning effectiveness difference between using PC alone and the combination of using PC and mobile devices. The research results showed that the users from the combination group had higher access frequency during supplementary learning time. Similarly, Sung and Mayer [16] compared students' learning performance on multimedia learning module of how solar cell works incorporated on different devices: a mobile device (i.e., iPad) and a desktop computer (i.e., iMac). It was observed that the mobile group had higher rating on self-reported willingness to continue learning than the desktop

group. This implied that the students with mobile devices had the more access to study at convenience, and mobile devices may trigger students' engagement in learning.

While learning laboratory experiment on mobile devices is not new, such topics were demonstrated in many studies (*e.g.* Bottentuit and Coutinho [17], Zervas, *et al.* [18] and Alkouz, *et al.* [19]). However, the drawback with some of these virtual laboratories is that they were either developed in 2D (may not visually represent the physical system in a realistic matter) or not very user-friendly (*e.g.* busy user interface, outdated software, complex installation or setup process). Therefore, in this paper, we aim to develop a 3D interactive user-friendly mobile app for an engineering laboratory experiment that can be easily distributed to any users who own a compatible android-based mobile device so that students can learn and practice the experiment procedure from anywhere and at any time. This would allow on-campus students to become better familiarized with the fundamental knowledge associated with the experiment and to be more prepared at the time of the experiment. This could lead to less time needed to complete the actual laboratory experiment and less wear and tear on the laboratory equipment. In addition, using mobile virtual laboratory would provide off-campus/distance-learning students with an opportunity to practice the experiment without being physically presented on campus.

### **3 Background**

This section provides a brief background information on the mechanical engineering laboratory experiment. It also delivers a short description of the virtual experiment we have done previously on different VR platforms.

#### **3.1 Undergraduate Mechanical Engineering Laboratory**

We chose the Jet Impact Force on Vanes (Jet-force) experiment in the junior level laboratory course (ME 305 Thermal-fluids Laboratory) at Old Dominion University (ODU) for the physical-to-virtual transformation. The experiment involves the determination of jet impact force arising from reversal of a water jet after hitting a vane. The equation  $F = Cm^n$  represents the relationship between force ( $F$ ), mass flow rate ( $m$ ) and type of vane ( $C$ ) [20]. Initially, a type of vane that includes a flat shaped vane and a funnel-like shaped vane with narrow mouth (both vanes have narrow stems) needs to be attached to a jockey-weight sliding beam mounted on top of the cylindrical lid. Once the machine is turned on, water then is discharged through a nozzle inside the transparent cylindrical storage tank to form a jet, providing impacts on the selected vane. The flow rate of the water jet can be set to three settings (low, medium or high mode) by adjusting a water valve. As the flow rate changes, the force from the water jet deflects the beam from the horizontal position. Hence, the jockey-weight can be slid along the beam to balance the beam position. The balanced beam is indicated by a blue tally line not exceeding the top surface of the cylindrical lid. As water keeps hitting 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 other shapes of vanes for several different mass flow rates. Figure 2 illustrates the physical set-up of the Jet-force experiment.



Figure 2: Physical Set-up of the Jet-force on Vanes Experiment.

### 3.2 Virtual Reality (VR) Engineering Laboratory

In previous studies, we have successfully implemented this particular experiment virtually on two large scale virtual environments namely the CAVE and the 3D TV [3]. The CAVE is a room-sized cube with three projection walls (front, left and right, each with dimension of 12' x 9.5') as well as the floor projection. A user can wear a pair of 3D glasses in the CAVE to view stereoscopic images on the projection walls generated by a computer. Compared with the 3D TV, multiple screens in the CAVE provides more level of immersion. Figure 3 shows comparison of the Jet-force experiment setup on the 3D TV and in the CAVE.

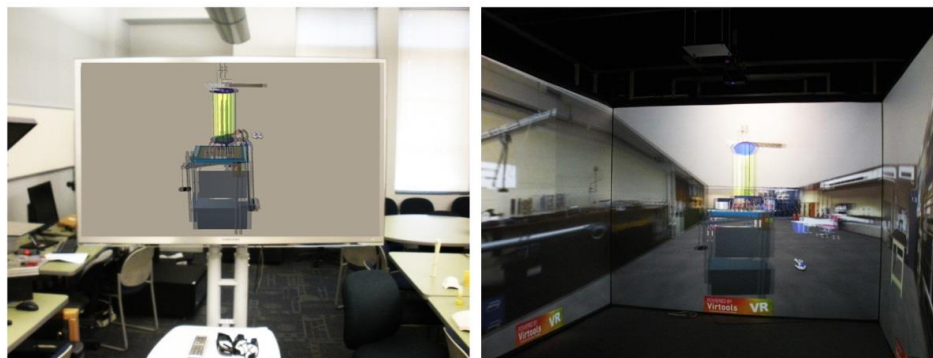


Figure 3: Virtual Jet-force Experiment on the 3D TV (Left) and the CAVE (Right) system.

The virtual experiment serves as a pre-lab session for students to practice prior to the physical laboratory experiment. During the virtual session, the students first take five minutes to review the virtual experiment instructions, and then proceed with virtual experiment using an input device (wireless Xbox gaming controller) for interactions in the virtual environment. Lastly, students walk through the experiment procedure step by step as they would have done in the actual laboratory experiment.

## 4 Methodology

Building a 3D interactive virtual laboratory requires the following design steps: (i) observing the physical system and understanding the general experiment procedure, (ii) creating the 3D model based on the physical system via computer modeling software, (iii) making the 3D model interactive and navigable by adding animations and input device control, and lastly (iv) deploying the finished project to an executable file.

### 4.1 App Design Objectives

To ensure the mobile app for the best user experience, it is important to limit the app memory (RAM) consumption to make sure that the app runs at an acceptable framerate with no significant delay. This can be done by optimizing the 3D model of the laboratory equipment such as reducing number of polygonal count. In addition, the virtual laboratory mobile app should be engaging and interactive. Users will be able to manipulate the 3D virtual equipment using the touchscreen with multi-touch technology (e.g. pinch two fingers on screen to zoom) to complete respective experimental tasks in the virtual environment. Furthermore, the user interface (UI) design of this mobile app should be simplistic and intuitive so that the user can familiarize with the interface quickly without spending extra amount of time navigating the app menu.

### 4.2 App Functionality

The overall goal of this current study is to develop a 3D interactive virtual laboratory that functions the same as the actual system. In other words, students should be able to achieve the same laboratory objectives when practicing on the virtual experiments. The desired functionalities are illustrated in the functional diagram in Figure 4 as follows:

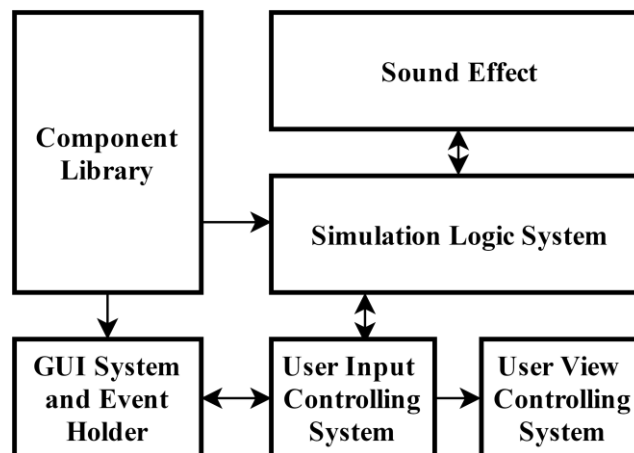


Figure 4: Functional Diagram of the Jet-force Laboratory.

The following paragraph explains each functionality block in detail:

- **Component Library** contains 3D models and 2D sprites. For example, the 3D laboratory equipment model (Jet-force) contains a few other 3D sub-components such as water tank, nozzle ruler, etc. 2D sprites include 2D elements such as UI icons.



- **Simulation Logic System** is the fundamental simulation system to model and simulate the control logic of the 3D virtual Jet-force equipment. The simulation system updates the simulation based on the current state of the Jet-force components as well as the status of the visual outputs represented by particle system or virtual physics.
- **Sound Effect** contains all the audio files including the sound effect from the virtual laboratory equipment and background music.
- **User Input Controlling System** allows users to make interaction with virtual objects and modify the input of Simulation Logic System.
- **User View Controlling System** provides five different perspective views for users to focus on a specific working area of the virtual Jet-force equipment. It includes close view, side view, up view, back view, and front view.
- **GUI Menu System and Event Holder** provides a comprehensive graphical user interface with a menu system and a toolbar. Furthermore, it monitors and manages the simulation event in the app.

## 5 Implementation

Two main software that we used to develop the virtual laboratory mobile app are the AutoCAD MAYA and Unity 5. AutoCAD MAYA is one of the leading 3D modeling and rendering software extensively used in gaming, film, 3D animation and modeling and simulation industries. It also provides various modeling and texturing techniques. Unity is a cross-platform development engine that has a large community-base for better user knowledge support. We chose Unity 5 as our main development engine for its graphic application program interface (API) support (Direct3D, OpenGL, Vulkan etc.) and its capability of deploying the finished project to different platforms (mobile devices, web browsers, desktop PCs and game consoles). In addition, Unity offers an intrusive way to develop and test scripts as behavior components. For instance, users can directly drag and drop a pre-written script in either C# or Java to a certain 3D virtual object in the scene to test its functionality or behavior.

### 5.1 Modeling Techniques

There are two common types of 3D modeling techniques: polygon and NURBS (Non-Uniform Rational Basis Spline) modeling (also known as curve modeling). Polygon modeling uses polygonal components such as vertices, edges and faces to illustrate surfaces of a given 3D model while NURBS modeling uses surfaces that are constructed by drawing two or more curves in a 3D space. Both techniques have pros and cons. Polygon modeling takes less time and less effort to model and render. However, polygonal modeling also has poor representing curved surfaces. On the other hand, NURBS modeling provides smoother and more accurate curved surfaces in terms of mathematical precisions. Compared with polygon modeling, NURBS modeling has less flexibility to edit the texture on the faces of a 3D model. In MAYA, we used polygon modeling to create components with simple shapes (polygon primitives) such as cube-shaped objects. NURBS modeling was mainly used to develop cylindrical such as wires and tubes.

## 5.2 Simulation Logic Design

Since there is a large number of virtual components in the 3D Jet-force model, creating a Simulation Logic System (SLS) to hold all the application objects is essential. The purpose of creating a SLS is threefold: The first goal is to store and manage all types of data for the various virtual objects, the second goal is to generate realistic virtual simulation logic for the application, and the third goal is to monitor various simulation events and modify them if necessary.

There are three types of simulation in the Jet-force virtual model: (i) water jet providing an impact force, (ii) balancing the weight of the water tank, and (iii) balancing the ruler/beam with a sliding jockey-weight. For dynamic water simulation, we used a particle system in Unity 5 to generate a water emission effect in a 3D environment. The water tank balancing simulation is controlled by the weight comparing function in SLS. After the user add weight to the scale, the virtual water tank elevates accordingly, just as how it is done in a real scenario. Finally, to simulate a bouncing effect of the ruler/beam component, we used two virtual hinge joints and one virtual spring joint, attaching on the hinge side of the ruler. The ruler object can rotate at certain angles based on the sliding jockey-weight position on the ruler.

## 5.3 User Interface Design






User interface (UI) focuses on user experience and interaction. A user-friendly, simple yet practical UI design is often critical to the usability of an mobile app. The primary design purpose of this app is to create an intuitive user interface to be aesthetically integrated with the educational theme. We use the gradient light blue color as the environment background as it offers a professional feeling to the audience and highlights the white graphical icons (as illustrated in Figure 5 below).



Figure 5: Three Main App Scenes  
(Main Menu Scene (top), User Guide Scene (bottom left), Experiment Scene (bottom right))

Figure 5 presents the three primary scenes for this mobile app. The first scene is the main menu scene, a starting scene where users will see after the launching app. Inside of this scene, users can either start the virtual experiment by sliding fingers across bottom portion of the screen or check the experiment tutorial guide by clicking on the “User Guide” icon. The second scene is the user guide scene, where users can walk through the experiment tutorial before they start the virtual experiment. Lastly, the third scene is the experiment scene. This is where users can interact with the virtual system and perform the virtual experiment. The UI icons on the lower left screen allow users to exit, restart, change settings, toggle sound on/off or switch the user view. The description is illustrated in Table 2.

Table 2: Icon Description in the Experiment Scene

				
Exit	Restart	Settings	Sound	View

#### 5.4 User View Design

The Jet-force experiment mobile app contains a total of five viewing angles/perspectives. Users can switch to any of the five views at will by tapping the “view icon”. This view switch feature saves users time by quickly locating the view camera to a specific working area of the equipment for users to complete a specific experiment task. By default, when entering the experiment scene, the view displays the complete setup of the virtual systems. Figure 6 shows the other four viewing perspectives. The top left screenshot shows on the jockey-weight sliding beam view while the top right shows the close-up vane view. The bottom left screenshot displays the valve view while the bottom right displays the bottom tank view.

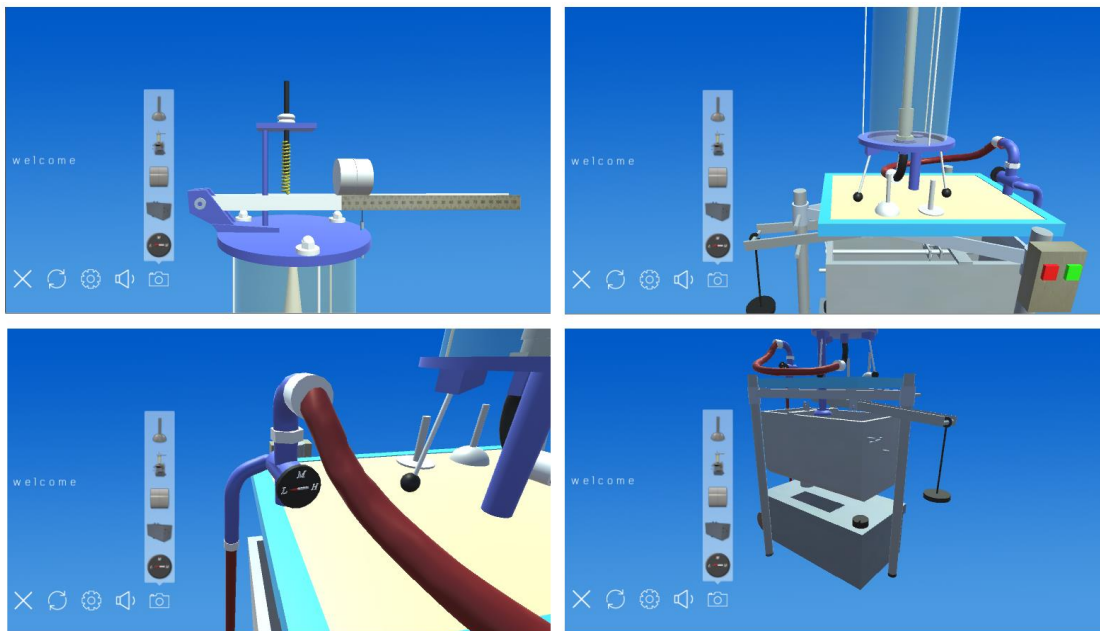




Figure 6: Viewing Perspectives in the Experiment Scene.

## 5.5 User Touch Gesture

Most mobile devices are capable of tracking up to five fingers touching the screen simultaneously (multi-touch). In this mobile app, we followed the standard gesture control mechanism for touch screen as shown in Table 3. Pan gesture was not implemented as this app offers five preset camera views for faster and more convenient viewing switch.

Table 3: Touch Screen Gesture

	
Tap (Select)	Spread/Pinch (Zoom)

## 5.6 Deploy Project to Android

Unity 5 offers a variety of options for developers to deploy finished project to desired platforms. If developers need to build and later deploy the project to Android-based devices, two SDK packages, namely, the Java Development Kit and the Android SDK Tools, must be installed. The finished project then can be built and deployed to a single executable .apk file (i.e. equivalent to .exe file on Windows platforms), which can be installed and run on any compatible Android-based devices (e.g. Android-based smartphone or tablets). It is also important to make sure that the “USB debugging” and “Install from Unknown Sources” options on the Android device itself are enabled so that the .apk file can be set up without any technical issues. Figure 7 illustrates the completed virtual Jet-force experiment on an Android-based tablet device.



Figure 7: Virtual Jet-force Experiment Demonstrated on a Tablet Device

## 6 Discussion

As mentioned in section 2, the main benefits of using mobile devices as learning tools are portability, easy accessibility and low cost. Unlike other e-learning methods or large-scale virtual learning environments, where they typically require students to be physically presented on site, mobile devices offer students an opportunity to learn asynchronously at anywhere and anytime. With respect to interaction, mobile devices do not require any sort of input devices (e.g. joysticks, gaming controller or keyboards), users can directly interact with mobile apps using the build-in touchscreen. In terms of portability, mobile devices weight much less than text books and laptops. They are easy to transport and carry around. Comparing with traditional learning methods, the interactive features of the mobile app make the learning session more interesting, more engaging and more exciting.

From the technical aspect, one issue with using mobile apps for learning is the screen and key size [21]. Users may find difficult to see certain things or to interact with certain tasks due to the small screen size. Thus, it is really important for the developer to keep this issue in mind and to ensure that the readability of the mobile app is reasonable. App compatibility is another issue that needs to be addressed. Currently the app is only compatible with Android 4.3 or above. Whether the app will run on earlier Android versions is untested. The app is not accessible for users who own non-Android devices (e.g. iPhone or Windows phone). From the social behavior aspect, using mobile devices as learning tools may cause distractions [22]. With social media, web browsing or gaming available, it is possible for some users to be distracted from paying attention to the learning materials on the mobile devices

## 7 Conclusion and Future Work

This paper illustrates the design and development of a 3D interactive mobile app for the undergraduate mechanical engineering laboratory – the Jet-force experiment, and describes the benefits of using mobile app as a learning source for hands-on tasks in engineering education. In addition, this mobile app not only provides distance learning and offline students with an opportunity to experience hands-on experience, but also offers on campus students to practice and to be familiar with the experiment procedure prior to physical experiment.

The future work of this project will include the following: (i) making this mobile app multi-platform compatible – we need to expand this app on other mobile platforms (iOS, Windows Mobile) to cater iPhone and Windows phone users , (ii) conducting a survey to evaluate the usability of this mobile app (planned for Spring 2018), and lastly (iii) comparing the study results from mobile app with the results from other VR platforms that we have studied such as the CAVE and the 3D TV.

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