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Building and Implementing an Economical Construction Equipment Simulator as a Virtual Reality Tool in the Classroom

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Virtual reality is a growing technology topic within the construction industry. Virtual reality cannot only provide entertainment, but it can be used for educational learning and training sessions. One key component of virtual reality incorporated into training sessions focuses on the simulation aspects where the environmental around a person imitates close-to real life conditions. Virtual reality simulations can take on many different forms such as a game, role-play, or even a training activity. Virtual reality through the development of construction equipment simulators has been used to help train construction equipment operators. Yet, the affordability of these simulators may not be within the budget of a company or educational institution. This paper discusses the basic components of a construction equipment simulator and provides insights into how a more economical affordable simulator may be built for the use of educational purposes.

Key Words: construction equipment simulator; virtual reality; hands-on activity; equipment management; construction technologies

Introduction

Once believed to be for entertainment purposes only, virtual reality (VR) and other realities are rapidly transforming into construction and civil engineering related fields (Goedert & Rokooei, 2016). These VR technologies are refining structural engineering building designs, expanding project management tools, improving educational curriculums (Martin-Cruz 2022; Maltese et al, 2016), and even integrating employee training sessions. Some examples includes interactive BIM models (Gheisari et al., 2016; Zhu and Issa, 2017), panoramic video technology for safety training (Sacks, et al 2013; Sacks, et al 2015), and training equipment operators with construction equipment simulators (Wang et al., 2004). Virtual reality takes on another degree of reality when simulations are incorporated into the experience.

Simulations add more detailed complexity to the virtual recreation of a scenario, situation, or process where a person almost believes what they are experiencing is actually happening in real life (Lucas & Gajjar, 2022; Olbina & Glicks 2022; Wang et al., 2011). In other words, the look and feel of an experience within a situation or process is key to the purpose of a simulation. This involves focusing on a person's five senses (sight, touch, sound, smell, and taste). And of the five senses, typically sight, touch, and sound are the most common central points to where simulations take place. Prerecorded noises of the situation can provide the sound component of simulation. Drafting virtual environments provides the visual component of simulation. Moreover, building physical objects provide both the visual and touch components of simulation. To illustrate this, a mechanical bull may be one of the most common and sometimes overlooked simulators. The experience of riding a bull through sight and touch can be simulated using a mechanical bull, where the use of hydraulics under some sort of semi-round object are designed to simulate the movement of a bull trying to buck a rider off. Prerecorded sounds of a bull can improve the sound component of the simulation. Yet, the senses of taste and smell of riding a bull have not only been non-focal points of mechanical bulls, but it can be a positive benefit of using a mechanical bull compared to actually riding a bull. As a result, using a mechanical bull can provide a safe, low impact environment for the bull rider.

Other types of simulators such as driving a car, flying a plane, and even operating a piece of construction equipment can be used for both educational and training purposes (Wang et al., 2004; Zhu & Issa 2017; Voordijk & Vahdatkhaki, 2022). These simulator training programs typically involves not only building the equipment to make up a simulator and developing the virtual software, but a training curriculum must be developed. This usually involves a team of personnel with different talents coming together to accomplish the objectives required for a particular type of simulator.

Construction Equipment Simulators

In the construction industry, virtual reality using simulation is being implemented within the realm of heavy construction equipment (Louis, et al. 2020; Wang et al., 2011). Construction equipment simulators have been developed for numerous types of construction equipment such as forklifts, cranes, skid steers, and bulldozer excavators. Most of these equipment simulators are made up of two components; the simulator station setup and the simulator software. The simulator station setup refers to the chair, controllers, computer, monitors, speakers, etc. The software for the simulator delivers the virtual graphics component for the simulator to be used.

The simulator station setup provides the initial physical experience of the simulator. The realistic feel of these simulators increase as more details are incorporated into the design of the simulator. Many types of heavy civil equipment have some sort of cab where the operator sits in a seat surrounded by the controls to operate the equipment. These controls may be joysticks, a panel of buttons, a wheel, and/or foot pedals depending on the specific construction equipment type. To accurately reflect the look and feel of a specific simulator, the controls are typically made to look like the controls from the actual piece of equipment.

The software for the simulator dictates both the system requirements for the computer and monitors. Typically, a higher quality graphics and storage of computers are required to run the software for simulators. Providing inadequate quality graphics can greatly diminish the simulation experience. Each type of construction equipment simulator can be used with an equipment specific curriculum to help training new operators or even highly skilled operators to gain more knowledge and skill in operating a certain piece of equipment. The traditional approach to training operators typically involves a crash course using the equipment and then learning by trial and error. This can be a dangerous process for both the operator, construction personnel in the area, and possibly anything in

the path of the equipment on the jobsite. The use of equipment simulators would be a cornerstone of taking the training process from being in a traditional jobsite setting and transforming the trainee's surroundings onto a virtual jobsite where common scenarios can be incorporated into this simulated training program. This more hands-on approach would allow the trainee to learn how to deal with these real-world scenarios in a safe environment.

Benefits of construction simulator

There are many benefits to using a construction equipment simulator. New operators can be not only a danger to themselves and the people around them, but new operators can commonly break the construction equipment. Simulators remove many problematic factors for new operators and creates a safe learning environment. Below are some benefits of using construction simulators (Louis, et al. 2020; Wang et al., 2011).

- Improve skills of both new and experienced operators
- Reduces time to learn operator skills
- Can provide an initial training curriculum
- Safe work environment
- Won't damage expensive construction equipment
- Reduces human error
- Allows operator to safely fail and try again
- May have multiple scenarios within training curriculum
- Adaptable training curriculum depending on the simulator metrics
- Simulators can be exciting and engaging for users

Unfortunately, the major hurdle for many desiring to purchase a construction simulator has been the initial cost. The costs of construction simulators in the current 2022 market were quoted to range between \$25,000 and \$120,000. The price of the simulator increases as more details are incorporated into the design of the simulator. A basic package at the lowest cost price may be a desk and chair setup with the controllers, software, computer, monitors, and audio speakers. Higher price points begin incorporating significantly more details into simulator such as a realistic looking cab setup with hydraulic powered motions. This cost range is also dependent on the specific construction equipment type where some more complex pieces of equipment use additional controls to properly operate. Unfortunately, this purchasing cost may not be in an organization's budget.

Scope of Work

The aim of this work was to design and build an economical simulator prototype from items commonly available. This occurred in a senior level undergraduate class about construction technologies. These students will design a construction simulator, put together a cost break down of materials for less than \$3,000, estimate a schedule to complete the build within 30 days, and give a presentation over their proposed simulator prototype design. This gives students a hands-on experience of not only using technology, but also building the technology. Then this simulator prototype will be used in another senior level undergraduate class focused on construction equipment management. This class will be required to use the simulator to complete work in a virtual environment and then complete a survey on the appearance of the simulator and how well this simulator prototype actually replicates the use of the construction equipment on a jobsite setting. This is a novel

Methodology

This research occurred in two construction classes, Technology in Construction and Construction Equipment Management, to complete this work. The students enrolled in the Technology in Construction class learned about various technologies used in construction. As a group project, the students were tasked at designing and building a construction equipment simulator prototype. Then students in the Construction Equipment Management class use this equipment simulator prototype, and then complete a student survey to determine the simulator performance of the prototype.

Curriculum of In-class Simulator Prototype Project Build

The students enrolled in Technology in Construction were assigned to break-up into groups, design a construction simulator, put together a material cost break down of the build, estimated schedule to complete the build on a Gantt chart, and give a presentation over their proposed simulator. The budget was less than \$3,000 and a build schedule time of no more than 30 days. This gives students a hands-on experience of not only using technology, but also building the technology. The students had three weeks to complete this assignment. After all students presented their designs to the class, the class provided discussion during lecture and voted on a which simulator design to build using an online surveying platform.

Curriculum of Homework Assignment Using Simulator Prototype

The students enrolled in the Construction Equipment Management course were assigned to use the simulator prototype. Before using the simulator prototype, each student answered questions about the appearance of the simulator using the student survey. Then each student was required to complete a series of tasks with the simulator prototype. A member of the research team recorded the time to complete the tasks, operator efficiency, and productive rate. After using the simulator, a post student survey was also conducted to provide feedback using the simulator prototype.

Developing a Student Survey

A student survey was used to help evaluate the performance of the simulator prototype. First, the survey asks about a student's experience as an equipment operator. The rest of these questions involved the appearance of the simulator, realistic use of the simulator, and possible improvements to the simulator. Each student evaluated each statement based on the following: strongly disagree = 1, slightly disagree = 2, neutral = 3, slightly agree = 4, strongly agree = 5. The average was calculated and then reported in the results.

Results & Discussion

The 43 students in the Technology in Construction class broke-up into 7 groups (6 students per group). Each group designed a simulator prototype, created a material item cost breakdown, and provided a projected schedule to build the simulator. A slide presentation was also constructed to communicate each group's design, cost breakdown, and estimated schedule to build. This was uploaded to the online classroom platform to be graded for content purposes. Then each group gave a presentation on their proposed simulator. Some groups elected one or more representatives to give the presentations. Other groups divided the slides equally among each group member. Each group had a logical vision of how to design and build their simulator prototype. Table 1 was constructed to provide a summary of each groups design setup, system, material cost, and projected schedule. From

the presentation, 4 of the 7 groups proposed a design setup using a cab due to the more realistic setup for a piece of construction equipment. A computer system was chosen for 6 of the 7 groups. The material costs for their prototypes ranged from \$825 to \$2,880. And the estimated schedule for each build ranged from 8 days to 30 days, which was largely variable due to complexity of their designs and estimated time to ship materials.

Table 1

Student Proposed Simulator Prototypes

Group	Design Setup	System	Material Cost	Schedule
1	Desk and chair	Computer	\$825	8 days
2	Desk and chair	Computer	\$1,206	13 days
3	Cab	Computer	\$1,968	27 days
4	Cab	Computer	\$781	28 days
5	Desk and chair	Computer	\$1,413	23 days
6	Cab	Gaming Equipment	\$951	9 days
7	Cab	Computer	\$2,880	30 days

Proposed Simulator Design to Build

After all the groups presented their proposed simulator prototype, an blind survey using an online platform was taken to determine which prototype would be built. The students in the class unanimously voted to use a modified design version based off Group 3. These proposed modifications incorporated other design ideas and material items from the other groups. This created a sense of belonging from all the other groups. Figure 1 shows the final simulator cab design and the cart monitor. The cab of the simulator was designed with largely 2x4 boards to provide framework for the cab. The platform cab of the simulator design used 2x4 boards with dimensions of 30 in. width by 48 in.

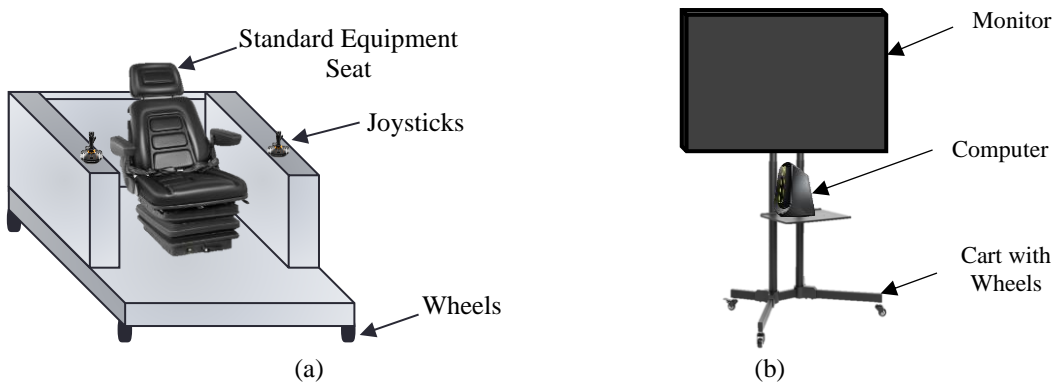


Figure 1 (a) chair cab and (b) cart monitor design of construction simulator.

The schedule for building the construction equipment simulator was estimated using a Gantt chart. This was broken down into 9 tasks. The ordering and shipping of the materials during this period of time was fluctuating due to supply chain issues. A suppliers of the materials reported up-to 14 days upon delivery for both the computer equipment and the construction cab seat. This ordering and shipping of material was the largest estimated duration for the build. It was estimated to take a week to build the frame of the chair enclosure for the cab and then 3 days for paint and add graphics to the

cab. The rest of the build schedule focuses on installing and adjusting the computer equipment and accessories. The total estimated build time was 29.5 days.

The total estimated material cost was \$2,034. Roughly, half of the estimated cost is the gaming type desktop computer at \$1,100. This higher cost compared to more traditional computer came from the high quality graphics and large memory of the gaming computer. Next, the 43 in. television monitor and simulator cab seat were each roughly \$260. The joysticks were quoted at \$130.

Process of Building the Construction Simulator

The materials for this simulator prototype were ordered and shipped to the university within 5 days of being ordered instead of the 14 days projected. A collection of students and the professor from the class fabricated the simulator cab using 2x4 lumber boards, ½ in. plywood, and ¼ in. plywood. A circular saw was used to cut the 2x4 boards to length and wood screws were used to secure 2x4 boards together. After building the framework of the platform, a table saw was used to cut the ½ in. plywood and wood screws were used to secure the 1/2 in. plywood to the deck of the platform. Then three sides of cab were framed with 2x4 boards. Lastly ¼ in. plywood was secured with wood screws into both inside and outside of cab sides. The cab had 3 coats of grey paint and then graphics of the university name, construction program, and university mascot with a hard hat were attached to the cab. This final construction simulator prototype is shown in Figure 2. The view from operator setting in the chair of the cab is shown in Figure 2(a) and a lateral view of the simulator prototype is shown in Figure 2(b). This simulator prototype was built in 10 days as estimated. Lastly, while the estimated material cost of the build was \$2,034, the actual total material cost of the build was \$2,180 to incorporate the costs of the graphic design on the simulator cab.



(a)



(b)

Figure 2 (a) view from chair in cab and (b) view of final construction simulator.

Software for the Construction Simulator

One of the biggest challenges with the simulator prototype was the options for simulator software and equipment. A desktop computer with large memory and graphics cards is required and preferred for most software. This type of computer is commonly designed for gaming applications and therefore is commonly referred to as a “gaming” computer. A popular gaming desktop personal computer was purchased for this simulator prototype. Multiple simulator software packages were downloaded onto

the desktop computer. When the research team conducted a trial run to ensure simulator was functioning properly, the team quickly noticed differences between simulator software packages. The capabilities of the software had a direct correlation between the cost, quality, and capabilities of the software. Some software only had the capabilities to use keyboards and mouse to operator software. Others had less developed graphics and lacked user friendliness. A popular gaming software package was chosen based on the joystick capabilities, high graphics, and reviewer comments online.

Using the Construction Simulator Prototype as a Hands-on Class Activity

After building the simulator, the simulator was placed in a classroom setting. Another class of 39 students enrolled in the Construction Equipment Management class used the simulator for the purpose of providing better insights into the challenges of using construction equipment. A survey was developed to evaluate the simulator and provide information about how experienced these students are using equipment. The survey was filled out by 25 students composed of 7 juniors, 14 seniors, and 4 graduate students. None of these students were required to fill out this survey for a class grade and the survey responses were filled out anonymously and not reviewed until course was completed.

To help better determine an initial student bias against equipment simulators, the students were asked before using the simulator, “Do you believe equipment simulators can closely replicate actual pieces of construction equipment?”. Figure 3 shows these student responses. The majority of the students agreed slightly or strongly that simulators could closely replicate a piece of construction equipment. However, only 1 student slightly disagreed. This indicates the students may not have a bias against equipment simulators.

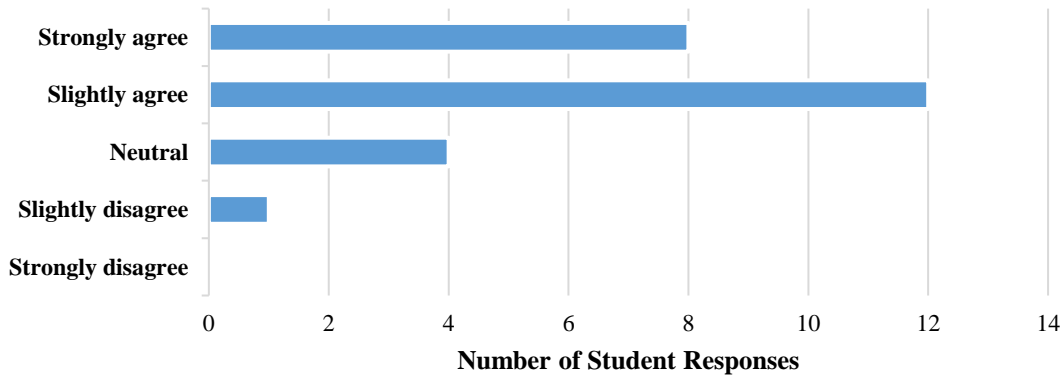


Figure 3 Student responses to the statement: “Do you believe equipment simulators can closely replicate actual pieces of construction equipment?”.

Each student used the simulator for a minimum of 15 minutes. Then these students evaluated the simulator by filling out an electronic survey. Each student evaluated each statement based on the following: strongly disagree = 1, slightly disagree = 2, neutral = 3, slightly agree = 4, strongly agree = 5. Table 2 shows the summary of the student survey. The average, minimum, and maximum of each statement response was reported. The overall average of the equipment simulator was a 4.10. This indicates the simulator was able to mimic a piece of construction equipment to a degree. The joystick and controllers had the lower rating of out the simulator components. This is due to a keyboard being used instead of the joysticks or steering wheel. Since the joysticks and controllers had the lowest rating for the simulator components, the overall experience of the simulator could be enhanced with improvements to the joysticks and controllers.

Table 2

Summary of Student Survey (based on 25 student responses)

Statement	Avg	Min	Max
Simulator looks like a piece of construction equipment.	4.08	2	5
Simulator operates similar to using construction equipment.	4.00	3	5
The joysticks and controllers of the simulator feel realistic.	3.76	2	5
The seat of the simulator feel realistic.	4.12	2	5
The sounds of the simulator sound realistic.	4.28	2	5
Software of the simulator look realistic.	4.24	2	5
Software of the simulator was user friendly.	4.24	2	5

Possible Improvements

Technology improvements is a reoccurring theme with most technologies including the invention of the wheel. This simulator prototype was able to provide some insight about using construction equipment within a simulated virtual environment. Multiple improvements could be made to enhance the feel of the simulator. Both the simulator software and joysticks were developed by the manufacture for the purpose of entertainment purposes in a gaming type environment. With lower ratings of the joysticks, future work could be completed on improving the feel and functionality of the joysticks. Additionally, different simulator software packages could be developed to provide a deeper experience into operating construction equipment.

Conclusions

An economical construction equipment simulator was built for educational purposes. This allowed the students enrolled in a class learning about construction technologies to actually design and build a cutting-edge construction technology using their skills learned from other classes such as design, material cost break down, and projected schedule. Also, it provided a safe environment for students enrolled in a class about managing construction equipment to better understand the challenges of using construction equipment. The following conclusions can be made off the results:

- An economical equipment simulator can be designed and built.
- Based on the student survey, the equipment simulator was able to simulate operating heavy construction equipment.
- The gaming software was able to provide adequate sound and graphics for the equipment simulation experience.
- The joysticks and controllers had the lowest rating for the simulator components. Improving the controllers of the simulator could improve the overall experience of the simulator.
- This was a successful senior design project.

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