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Case Study: Developing and Implementing VR Technology for Civil Engineering Education

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Case Study: Developing and Implementing Virtual Reality Technology for Civil Engineering Education

Abstract

Virtual reality (VR) technology for engineering education has been shown to produce positive learning outcomes such as improved understanding of class concepts, increased motivation to learn, and higher accessibility. Despite these benefits, VR use in engineering education is limited, due to a limited understanding of the VR development and implementation process for a classroom. Therefore, the objective of this paper is to assess lessons learned from developing and implementing a VR module focusing on design choices for a senior-level structural engineering course. The development process for the VR module is presented along with tips and tricks for more effective development and a focus on civil infrastructure. Additionally, the implementation process for deploying the VR module in a classroom is introduced with advice for successful integration into the course. Challenges and successes of using VR for engineering education are highlighted and discussed in depth. From this research, faculty will be able to effectively develop and implement VR in their classes for improved learning outcomes.

Introduction

Virtual reality (VR) technology, characterized as a simulated three-dimensional environment enabling real-time interaction within a digital realm, has transformed numerous sectors with its immersive and interactive features. Although virtual reality originated in gaming and entertainment, its applications have rapidly broadened to include healthcare, automotive, architectural, and military training [1]. In healthcare, virtual reality simulations enable medical students to rehearse surgical procedures, thereby improving their skills in a low-risk, controlled setting [2]. This technology has been employed in therapeutic contexts, where immersive simulations assist patients in surmounting phobias and fears [3]. Rizzo et al. [4] investigated virtual reality as a mechanism for military training, specifically in combat simulation and stress-induced decision-making, concluding that virtual reality facilitates effective, immersive training that improves readiness and situational awareness without real-world hazards. In architecture and construction, virtual reality allows designers and clients to digitally examine building plans, offering insights into designs prior to the commencement of construction [5]. Despite the growing adoption of VR technology in education, particularly in disciplines requiring spatial awareness and technical comprehension, its application remains notably limited in many study areas. This gap highlights a critical need for broader integration of VR as a tool to enhance hands-on practice, which continues to be a cornerstone for improving student engagement and understanding across diverse academic fields.

The use of VR in education offers distinct advantages that traditional teaching methods often struggle to provide. By enabling students to interact with 3D models, manipulate objects, and experience scenarios in immersive settings, VR supports experiential learning and aids in knowledge retention [6]. Research has shown that VR can increase motivation by fostering a dynamic, interactive environment that encourages active participation. For example, a study by Anjos et al. [7] demonstrated that VR improved student engagement and learning outcomes in engineering education, while Alhalabi [8] found that students in VR-based environments exhibited higher retention rates, and a stronger grasp of complex concepts compared to those in traditional classrooms. Radianti et al. [9] also confirmed that VR's immersive qualities make it an ideal medium for challenging subjects, as it enables students to observe and understand processes that are difficult to visualize on white board or on slides. These studies underline the potential of VR to transform educational practices, making it a powerful tool for fostering conceptual understanding, practical skills, and collaborative learning.

In civil engineering education, virtual reality applications have demonstrated significant potential by enabling students to see and engage with large-scale infrastructure projects in manners that would otherwise be logistically impractical. Henstrom et al. [10] assessed the efficacy of virtual reality in augmenting the educational experience in civil engineering via immersive building inspections. The study revealed that virtual reality markedly enhances student engagement and comprehension of structural layouts and material properties, as well as the structural responses of buildings under stress, without elevating cognitive load, thereby positioning it as a promising pedagogical instrument. Similarly, Kassem et al. [11] assessed the application of VR technology in civil engineering education, finding that VR enhances students' understanding of complex infrastructure concepts and improves engagement compared to traditional methods. De Amicis et al. [12] in their study aimed to advance STEM cyberlearning by integrating cross-reality environments in smart buildings, finding that such immersive and multimodal systems enhance data literacy and engagement among users by making complex environmental data more accessible and understandable. These applications of VR in civil engineering not only enhance spatial and conceptual understanding but also prepare students for real-world challenges by simulating professional scenarios and encouraging hands-on learning experiences.

Despite these benefits, VR's adoption in civil engineering education has been limited by several practical and logistical challenges. This technology can involve considerable initial costs, limiting access to only those with substantial resources. Additionally, both educators and students may face a steep learning curve to effectively use VR systems, which can take time away from core learning objectives [10]. Another challenge lies in scalability; VR systems are often designed for individual or small-group interaction, making it difficult to accommodate large classes, which are common in civil engineering programs. Prolonged VR use can also lead to user discomfort, such as eye strain, motion sickness, and cognitive overload, potentially limiting its effectiveness in extended learning sessions.

Critical factors contributing to VR's underutilization in civil engineering education include the lack of established integration strategies, clear guidelines, and well-designed practical examples for incorporating VR into academic frameworks. This gap motivates the adaptation of structural engineering concepts to the VR domain to create opportunities to make advanced topics more accessible and engaging for the students, ensuring that VR remains a valuable tool in civil engineering education. This paper aims to bridge the gap in VR application in engineering education by providing a case study on the development and deployment of a VR module for senior-level civil engineering students. The specific objectives of this study are:

- Outlining the process of creating an effective VR module tailored to civil infrastructure topics.
- Sharing insights and techniques for developing VR content that enhances student learning.
- Providing a practical guide for faculty to integrate VR smoothly into their courses.
- Detailing both the successes and challenges encountered in VR integration.

Through these objectives, we aim to equip instructors with the knowledge and strategies needed to adopt VR effectively, ultimately contributing to improved learning outcomes and fostering a more interactive, engaging educational experience for students.

Development of Virtual Reality Module

Development of a custom VR module can be a time consuming and complex process. However, the following guidelines and tips can make the process easier. There are four main steps to the proposed framework: 1.) Determine the learning objectives that will be targeted by VR modules; 2.) Convert the lesson plan to an outline for the VR module; 3.) Implement the lesson plan into a minimum viable product (MVP) to ensure that the module accomplishes the target objectives; 4.) refine assets to improve the realism of the VR module. The custom VR module development cycle was about 2 semesters per module using a real structure and involved hiring computer science students and civil engineering students to develop the modules.

First, the learning objectives for the desired course content must be determined for the VR module. For instance, for a senior level civil engineering course, the goals for the VR module were to better enhance students' visualizations of beam design and how the material, shape, and size of a beam affect the deflection and the utilization ratio of the beam. The instructor noticed that students were not accurately understanding how the material, shape, and size of a beam affects the deflection and utilization ratio of that beam. Therefore, the instructor wanted to create a VR module to allow students to visualize and interact with different 3D models of a beam to visualize the deflection and utilization in real time. After the goals are established, a general lesson plan needs to be laid out. The lesson plan is an outline of topics that need to be covered. In the same example, the lesson plan involved teaching students three topics: 1.) Choosing a beam material, shape, and size; 2.) Visualizing the deflection of a beam; 3.) Determining the utilization ratio of a beam.

Once the objectives and lesson plan are established, the lesson plan needs to be translated into mechanics for the module. Mechanics are how players and the module, including states, challenges, rules, goals, actions, and strategies, interact with each other in a meaningful way that creates consequences in the immersive module [13]. For example, for the developed beam design VR module, the player interacts with a series of dropdowns to choose a material, shape, and size for their beam. Then, once a material, shape, and size are chosen, the virtual world updates by showing the beam deflection as a 3D line with a filled area, the max deflection as text above the beam, and the utilization ratio of the beam on a static panel. If the player chooses a different combination, then the deflection, max deflection, and utilization ratio all update accordingly. Figure 1 shows an image of this mechanic in the developed beam design VR module. Also, in a previously developed VR module to teach building system components and forces [14], the overarching mechanic chosen was a narrative walkthrough of the topic material, utilizing 3D visualizations and corresponding panels of text to convey information. This way, the content was being delivered in a sequential manner while providing 3D visualizations for the player to explore. More details about the building system components and forces VR module can be found in [14]. Additional functionality could also be added for a more interactive feel. For instance, in the building system components and forces VR module, the ability for the player to hit a button on one of the controllers to show / hide the architectural features was implemented. This ability provides another opportunity for interaction and can help the player differentiate between architectural components and structural components.

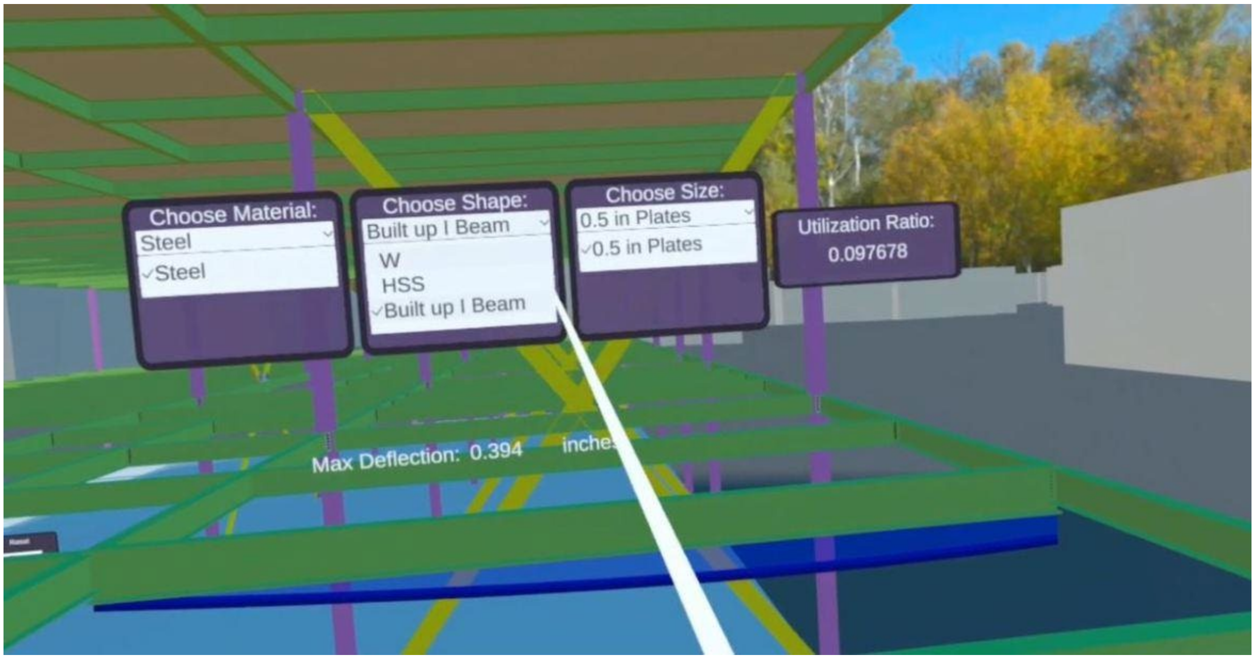

Figure 1. Screenshot of the developed beam design virtual reality module for design choices.

A major mechanic that must be determined is how the player will move the character. Some may choose to give the player the ability to walk around by walking around in real life. However, in our past experiences, we've seen that this movement can cause worse nausea and motion sickness as well as pose a safety issue as students may walk into furniture or trip over other objects. Additionally, there was not sufficient physical space in the classroom for 15 students to walk around in VR safely. Therefore, we chose to have the player remain fixed in real life and mainly move around in the game via teleportation by clicking on a button. For smaller in-game movement, the player may move the left joystick of the VR controller. This fixed physical position allows the player to look around and interact with the model without potential safety issues or worsening nausea.

Next, the mechanics must be implemented into a minimum viable product (MVP) to ensure that the module accomplishes the learning objectives. A minimum viable product is the minimum version of a product that can be used for concept validation, market viability, and audience feedback [15]. In the context of game development, an MVP is typically a game with only the mechanics implemented using simple shapes: no aesthetic graphics, no special effects, no sound effects or animations. The idea is to then use the MVP to get feedback to see if the mechanics work as intended, if the goals of the project are met, and if the game is fun. This step is where one chooses a game engine and starts coding the game.

For this research, we examined three prominent engines to potentially use: Unreal Engine [16], Unity [17], and Godot [18]. All three engines have VR development capabilities. First, the level of realism desired for the 3D graphics was determined. For 3D graphics, Unreal Engine is superior and has much more flexibility for realistic and stunning materials and 3D models compared to Unity and Godot. If realistic graphics are important for the module, then Unreal Engine may be the best choice. Next, the experience of the development team was considered. Godot uses its own custom language whose syntax is like Python. Unity uses C#, while Unreal Engine uses C++ and Unreal Blueprints. Unreal Blueprints are essentially node-based programming and may be easiest for non-programmers. Afterwards, research into other factors for each engine was completed, such as the number of community resources and the royalty structure. For the beam design VR module, Unity was chosen for its capabilities and ease of use. No matter which engine is utilized, all three are great choices.

After an engine has been chosen, the game must be coded and created. The game engine that is chosen will have documentation online that will be helpful in the game development process. Additionally, there are many tutorials online on how to implement a wide range of mechanics. Having knowledge in game development, data structures and algorithms, and computer graphics, can also help the process. For a civil engineering context, one may want to import building data from a common building modeling software such as Revit into Unity. To achieve this import, the authors used a Revit to Unity plug-in with already existing building plans of a building on campus. This process saved our development team from having to build a building from scratch and was the main motivation for using a building we already had plans for. Additionally, for a civil engineering context, one may want to connect external data sources such as structural analysis results by first saving the data to a .csv file and then loading the .csv file in Unity using the TextAsset class and Resources.Load() function. This class and function work with Android files (.apk), which many VR headsets use. Note, not all file readers and loaders work with all platforms.

Finally, assets and polish must be added to make the VR module aesthetic and appealing. One can find countless 3D assets and special effects online. Some prominent stores include the Unity Asset store and the Unreal Engine Marketplace. With online assets, one must check the allowed copyright use and any royalty agreements. Typically, royalties will only apply if the game is sold for profit. One can also create their own 3D assets using 3D art software such as Blender, Maya, and Houdini. However, creating 3D art can be time consuming.

A technique that can help reduce the effort needed to create 3D art is procedural generation. Procedural generation allows the user to quickly create 3D models using an algorithm at runtime rather than manually creating the model [19]. For the beam design VR module, a procedural generation technique was developed to generate beams of varying shapes and sizes at run time. Whenever a player selects a beam material, shape, and size from the dropdowns, the algorithm extracts the needed beam dimensions from a .csv file. Next, a 3D mesh is automatically generating by positioning the vertices and creating the faces to result in a beam mesh that matches the required dimensions. This process is done during runtime of the app and prevents the need for a custom-made beam mesh for each desired option. This process also allows for easier scaling of the application for new beam sizes.

Additionally, for the beam design VR module, all members and diagrams were color-coded consistently to allow the player to make connections and highlight the items we wanted to emphasize within the model. For instance, in Figure 1, all beams and girders are green, all columns are purple, all cross-bracing are yellow, and all deflection diagrams are blue.

Also, for the beam design VR module, a background was provided to provide a sense of enclosure and produce a more comfortable environment to interact with. For example, in Figure 1, trees, other buildings, and a sky can be seen in the background. To reduce emphasis on the background items, they are not as detailed as the main building.

Course Context

These VR modules were developed for an undergraduate senior-level civil engineering course focused on building systems. The main objective for the course is to transition students from component design to a system-level thinking. This objective is well suited for a VR situation where students can see in 3D how all the components of a building fit together. This well-suited match is what motivated this research. The authors noticed that students struggle with building system concepts and wanted to appeal to a different learning style preference via VR. The first set of VR modules developed focus on load path through a structure in 3D and the second set of VR modules currently being developed focus on component design using the building loads. The authors wanted to develop VR content to supplement student learning on these topics and give them experiences in a structure to illustrate these concepts.

Implementation of Virtual Reality Module

For the implementation framework of the VR module within the classroom, the steps are the following: 1.) Determine how many headsets are needed and how long each student will spend in the module; 2.) Acquire the headsets and set them up before class; 3.) Demonstrate how to use the VR headset and navigate in the model; 4.) Supervise the use of the VR module; 5.) Apply the knowledge gained by giving a quiz or having another activity; 6.) Charge and put away the headsets.

First, the number of headsets needed and how long each student should spend in the module must be determined. This step will be heavily dependent on how many headsets are available, the number of students in the class, and the length of the module. The authors found through experience that it is best to have 1 headset for every 3 students. Regarding length of time in the VR module, for the previously developed VR module to teach building system components and forces [14], through preliminary IRB investigation, students were told they were allowed to explore the module as much as they wanted on their own and their time within the module was tracked. Students were found to be averaging between 5 minutes and 20 minutes to explore the VR module. As more content was added, the researchers completed the VR module and timed the experience to determine a rough estimate of the module length. Combined together, it was determined that a time of 15 minutes given to each student to explore the VR module would be sufficient for most students. With a headset for every 3 students, 45 students could get through the VR module in an hour class period including the initial demonstration. Additionally, through preliminary IRB investigation, it was found that 5% of students chose to opt out entirely. These students would need to be provided an alternative assignment or activity in place of the VR module.

Next, the headsets must be acquired and set up before class. The authors purchased 15 Meta Quest 2 headsets in 2022 for $399 each through an education grant. These headsets were chosen as the cheapest and most effective headsets compared to other headsets at the time. After the headsets are acquired and the time comes to deploy the VR module, it is important to before the class starts and students arrive: 1.) Ensure all headsets are sufficiently charged, 2.) Have the VR headsets set up around the classroom, 3.) Have a plan for rotating students through the headsets to expedite student use, 4.) Have each headset powered on, set up, and the app launched, and 5.) Have accommodations for students with glasses such as having a few headset extenders available.

Then, at the beginning of class, it is best to give a demonstration of how to use the VR headset and navigate the module. Many students may not have any prior experience with VR or have any experience with this headset model, so it is important to show how to properly put on and use the particular headset that will be used. Instructors may demonstrate in real time by showing how to put on the headset, casting their VR screen to a projector, and showing how to navigate the VR module and use the VR controls.

After the demonstration, students will start working through the VR module. Some students may be uncomfortable with the VR module for a variety of reasons, including an uncomfortable fit of the headset and motion sickness. For this example, a couple of students expressed not being able to fit the VR headset over their glasses, even with the official VR glasses extender on the VR headset. Additionally, a couple of students expressed motion sickness within the first couple of minutes of using the VR headset and could not engage with the module. Note, some students may be sensitive to lights and 3D graphics. These students may need a replacement assignment in place of the VR module.

Once all students have worked through the VR module, it is important to have them apply the knowledge they have gained through a quiz or another activity. For the previously developed VR module to teach building system components and forces [14], quizzes were given based on the VR module content to reinforce learning. The quizzes contained homework type questions and were typical evaluations of learning assessment for structural analysis.

Finally, after the conclusion of the VR module period, the headsets need to be charged and put away. It is best to close the app and turn off each headset. One may need to ensure each VR set is complete and has all the pieces including the headset, the controllers, and any accessories. Also, one may keep the original box for each headset to keep each headset organized and ensure no piece is lost. Additionally, each headset may need to be charged for next time.

Conclusions & Lessons Learned

The use of virtual reality (VR) can be an effective tool for teaching concepts in civil engineering. To effectively use VR, development of a custom VR module facilitates addressing specific learning objectives. Development of the VR module requires careful consideration of the desired goals and lesson plan to determine the mechanics in the VR module. Movement and transition mechanics must be implemented in the chosen game engine with added aesthetic 3D models, sound effects, and polish. Once the VR module is developed, it can be deployed in class by determining the time per student and the number of headsets needed, setting up the headsets, demonstrating how to use the VR headset, supervising the use of the VR module by the students, applying the knowledge gained via typical learning assessments, and putting away the headsets. During this implementation, the prior experiences and comfort levels of the students must be accounted for to ensure a smooth process.

Several major lessons were learned throughout this research. First, consider a fixed physical position for the player to avoid potential added motion sickness and potential safety issues. Next, importing a building from a building modeling software like Revit to use in the module can be advantageous for civil engineering VR modules. Then, connecting structural analysis results such as those from SAP2000 to the module can be done via a .csv file and a file reader in Unity. Afterwards, consider utilizing procedural generation for 3D modeling to reduce the workload for creating 3D assets. Also, do not assume that all students will love VR technology or know how to use it. Additionally, do not forget to have the students apply the knowledge gained during the VR module through a quiz or another activity to reinforce their learning. In future work, the authors plan to gather data to quantify the effectiveness of the beam design VR module on student learning. Following these frameworks, faculty will be able to develop and implement their own custom VR modules in class to teach civil engineering concepts.

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AI-Assisted Technologies Disclosure

In this paper, ChatGPT was used to enhance the coherence and flow of ideas presented in the introduction section. This use of AI was limited to improving the connectivity of the text and did not influence the content, interpretation, or conclusions of the research. The final version of this article has been critically reviewed and further refined by the authors, ensuring that the content aligns with the authors' intended scope and scholarly rigor.

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