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Development of a Virtual Reality Game to Enhance Understanding of 3D problems in Engineering Mechanics Statics

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Her primary teaching objective is to foster a lifelong learning mindset in her students by promoting critical thinking and problem-based learning. Dr. AbdelGawad's teaching philosophy integrates real-life ethical dilemmas to encourage students to think deeply, challenge their opinions, and integrate ethics into their coursework to help shape them into successful, professional and socially responsible engineers.

DEVELOPMENT OF A VIRTUAL REALITY GAME TO ENHANCE UNDERSTANDING OF RIGID BODIES IN ENGINEERING MECHANICS STATICS

I. Background

Engineering Mechanics is a foundational course that is taught at the sophomore level in mechanical engineering curricula. The course explores the principles governing the effects of forces on stationary and moving bodies, with a primary emphasis on statics (the analysis of forces on bodies at rest), dynamics (the study of forces on bodies in motion), and mechanics of materials (the behavior of materials under various forms of stress and strain).

Core topics addressed include force vectors, equilibrium, structural analysis of trusses and frames, moments of inertia, and internal force distribution within materials. Proficiency in these areas is essential for success in advanced courses that focus on the design and analysis of mechanical systems such as Solid Mechanics in Mechanical Design, Design of Mechanical Components and Systems, and Finite Element Analysis in Mechanical Engineering.

II. Academic Challenge

Students in engineering disciplines frequently encounter difficulties in visualizing three-dimensional (3D) objects and spatial relationships, which are critical for understanding complex concepts such as forces, moments, and the behavior of rigid bodies in 3D space. Spatial visualization, defined as "the ability to generate, retain, retrieve, and transform well-structured visual images" [1], is an essential skill in STEM education and is closely linked to academic success. In engineering, particularly in fields like computer-aided design (CAD), the ability to mentally manipulate 3D objects is fundamental [2]. For mechanical engineers, this skill is indispensable for tasks such as designing intricate mechanical systems, analyzing stress and strain distributions, and understanding the motion of rigid bodies. The capacity to visualize spatially enables engineers to predict the behavior of objects in various environments and to solve complex problems involving forces and motion effectively.

However, many engineering students struggle to develop strong spatial visualization skills, a challenge attributed to several factors. These include limited exposure to hands-on learning activities, increasing reliance on digital devices that predominantly support two-dimensional (2D) interactions, and traditional teaching methods that often emphasize abstract representations. The growing use of devices such as iPads and digital notebooks, while offering significant advantages, has inadvertently limited opportunities for students to engage with three-dimensional spatial reasoning. These tools primarily confine interactions to a 2D plane, hindering the development of critical spatial thinking skills. Educators have noted that freshman engineering students often face difficulties visualizing and interpreting engineering models, underscoring gaps in their ability to mentally manipulate and process 3D objects [2]. Conventional methods, such as textbooks, physical models, and traditional modeling techniques, have proven insufficient in addressing these challenges and fostering the spatial visualization skills necessary for success in engineering [2].

III. Visualization Efforts

To address this challenge, researchers have explored various methods to improve student visualization skills, including physical object manipulation, computer-aided sketching, web-based games, dynamic geometry software (DGS), augmented reality (AR), and virtual reality (VR). The use of physical object manipulation involves hands-on activities where students interact with real-world objects. Computer-aided sketching allows students to create and manipulate 3D models on a computer screen using software tools like AutoCAD and SolidWorks. Interactive online games specifically designed to improve spatial reasoning skills can be a fun and engaging way for students to learn. Tools like GeoGebra and Cabri 3D, dynamic geometry software, allow students to construct and explore geometric shapes in a dynamic environment, fostering a deeper understanding of spatial concepts.

On the other hand, augmented reality (AR) overlays computer-generated images onto the real world, enhancing the user’s perception of reality. In education, AR can be used to create interactive learning experiences where students can visualize and manipulate 3D objects in their physical environment. For instance, an AR application could allow students to view a 3D model of a rigid body superimposed on their desk, rotate it, and explore its different parts. Martin-Gutierrez et al. [3] developed an augmented reality (AR) application for teaching engineering graphics concepts, replacing traditional materials such as textbooks, paper-and-pencil methods, SketchUp modeling, and online web-based exercises [4], [5]. The application incorporated AR technology, a USB camera (QuickCam Pro 9000), AR-Dehaes software, and computer vision techniques to display 3D models. Using the AR book, students could visualize 3D models on a computer screen by capturing images from the book, and the application included videos and exercises to explain orthographic concepts and freehand sketching. The experiment included mental tests (DAT-5: SR Level 2 and MRT) and a survey to assess the application's usability and student satisfaction. Results indicated that the AR training system improved students' spatial ability and received positive feedback. However, the system had limitations. It focuses on teaching 3D perspective drawing and projection views, tasks that can be performed more efficiently using computer software. Additionally, the AR system lacked features for real-time interaction with 3D models, such as rotating, translating, or zooming, leaving students reliant on traditional tactile learning methods for a complete understanding.

Recent research has shown that VR is a particularly promising tool for improving spatial visualization skills [6], [7]. The immersive and interactive nature of VR allows students to experience spatial concepts in a more concrete and engaging way, leading to improved understanding and retention [7], [8]. For instance, one study investigated the efficacy of virtual reality (VR) technology in enhancing spatial abilities among multimedia engineering students [9]. Using the Purdue Spatial Visualization Test—Rotation (PSVT-R), the researchers evaluated students’ capacity to mentally manipulate 3D objects before and after an intervention. Participants were divided into an experimental group, which utilized VR goggles with smartphones, and a control group, which employed traditional computers. Both groups engaged in structured training activities and free navigation exercises involving 3D models. The results revealed a statistically significant improvement in spatial ability for the experimental group compared to the control group. The findings support the potential of VR as a cost-effective tool for enhancing spatial reasoning skills, particularly in fields requiring strong spatial visualization [9].

VR games, specifically, offer several advantages for enhancing student learning including enhanced engagement and motivation, active learning, immediate feedback, and personalized learning [8]. VR game teaching can break through the limitations of traditional teaching and optimize the potential of existing teaching methods [10]. VR games can provide students with a personalized learning environment and bring innovation to traditional teaching classes, stimulating students’ interest in learning, all of which can further enhance immersion and exercise students’ abstract ability [10]. In addition to improving spatial visualization skills, VR has also been shown to enhance student engagement and learning experiences in a variety of other subjects [8]. By leveraging the power of VR games, educators can create immersive and engaging learning experiences that help students develop a strong foundation in spatial visualization and other critical engineering skills

Therefore, there is a need for an educational tool—such as a Virtual Reality (VR) game—that provides immersive 3D experiences to enhance students' ability to visualize and interact with 3D objects, thereby improving their comprehension of fundamental engineering mechanics concepts. The current work-in-progress (WIP) provides a basis for developing a Virtual Reality (VR) game that aims to enhance student understanding by providing an immersive, interactive environment to visualize and engage with these fundamental principles

This study introduces a prototype (Proof of concept) VR game designed to enhance students' comprehension of 3D rigid bodies, vectors, position vectors, and the translation of forces and moments. By immersing students in an interactive virtual environment, the game addresses the gap between theoretical principles and practical visualization, fostering deeper spatial understanding and problem-solving skills.

*IV. **Anticipated Learning Outcomes***

1. **Enhanced Spatial Visualization**: Students will develop the ability to visualize and manipulate 3D vectors, forces, and moments within a virtual space, improving their understanding of how vectors define points in three dimensions.

2. **Understanding Force Representation**: Learners will comprehend how forces and moments are represented and resolved in 3D space using direction angles. They will gain proficiency in translating forces and moments to different points on a rigid body, reinforcing their understanding of the statics principles.

3. **Rigid Body Analysis**: Students will apply statics principles to analyze rigid bodies, calculate resultant forces and moments, and evaluate the equilibrium conditions for rigid bodies in 3D. This hands-on interaction with rigid bodies will deepen their comprehension of equilibrium and force balance.

4. **Application of Theoretical Concepts**: Through interactive gameplay, students will apply theoretical knowledge to practical scenarios, advancing from basic force applications to complex systems like frames and trusses, where internal force representation is required.

5. **Increased Self-Efficacy**: The immersive VR experience is designed to boost students' confidence in their ability to understand and apply statics concepts. Pre- and post-assessments will measure their improved ability to resolve forces in 3D space, highlighting increased mastery of the subject matter.

V. Research Questions:

Our main research question is: How does How does the development and implementation of a Virtual Reality (VR) game enhance undergraduate engineering students' understanding of 3D rigid bodies and fundamental statics concepts? We will focus our research question based on student learning of equilibrium of 3D rigid bodies and students' insight on their experience using virtual reality. Hence, we have also identified three subordinate research questions:

1. How does the immersive and interactive nature of the VR game impact students' spatial visualization skills compared to traditional teaching methods?

2. What specific features of the VR game contribute to the understanding and application of force and moment translation in 3D space?
3. How do students' engagement, motivation, and confidence in learning statics concepts change through the use of the VR game?

VI. VR Development and Course Integration

Integration into the course and enhancement of student understanding of equilibrium of rigid bodies is going to be carried out in four phases:

- <u>Phase 1: Asset Creation:</u> 3D models will be created in SolidWorks and blender environments and exported for use within Unity, which will be used as the primary development platform for the VR game, allowing us to create immersive 3D environments where students can interact and visualize engineering mechanics concepts. It enables us to import and integrate 3D assets designed in SolidWorks and Blender, facilitating the development of detailed models of rigid bodies and force vectors. Utilizing Unity's XR Interaction Toolkit, we can implement interactive user interfaces and controls, providing an engaging and intuitive experience that enhances students' understanding of statics principles. Additionally, Unity will allow functions such as manipulating vectors and observing real-time changes to understand force translation and vector resolution.
- <u>Phase 2: Interactivity and User Interface Implementation</u> provide immersive experience with force trajectories and object manipulation. Students will be provided with a 360-degree perspective, enabling them to view and interact with rigid bodies from all angles. Through interactive manipulation, students can apply forces to objects and receive immediate visual feedback on how these forces affect the rigid body, reinforcing the cause-and-effect relationship essential in statics. As the game progresses, students face increasingly complex challenges, starting from basic force applications and moving to more advanced systems, such as trusses in 3D space, that mirror the course's progression. By simulating real engineering problems, the VR game will enhance the relevance of statics concepts, boosting engagement, retention, and the practical application of knowledge.
- <u>Phase 3: Educational Content and Game Development:</u> Assign the game as supplemental learning, with levels aligning with core course topics. A game narrative immerses students in progressively complex scenarios, requiring them to apply statics principles to advance, reinforcing their learning through interactive practice.
- <u>Phase 4: Assessment and Future Expansion</u> through utilizing in-game assessment tools to gauge understanding before and after VR interaction. Feedback from these assessments will guide the creation of additional content, including more advanced topics such as internal force representation, machines, frames and complex structures like cranes.

It is worth mentioning that the development of the VR game, including 3D asset creation, interactive features, and educational content, will be designed by undergraduate students under the supervision of lab instructors and software engineers within the college. This approach provides students with a valuable opportunity to apply their theoretical knowledge to a practical project, enhancing their skills in game development, software engineering, and educational design. Furthermore, the process of designing and implementing the game provides a deeper understanding of engineering mechanics concepts, as students translate complex theoretical ideas into functional, interactive learning tools. Moreover, this hands-on experience promotes creativity, teamwork, and problem-solving abilities, preparing students for future challenges in their academic and professional careers. By actively involving students in the project, the initiative not only advances their technical and conceptual understanding but also contributes to the development of an innovative educational resource that aligns with the objectives of engineering pedagogy.

VII. Preliminary Results

As part of an undergraduate Statics course, students were assigned a project to design, build, and analyze a crane using the PASCO Advanced Structures Kit. The project aimed to strengthen their understanding of fundamental statics concepts, including force analysis, equilibrium, and internal forces. Students were required to submit a comprehensive design report, deliver a presentation, and provide an individual reflection on their learning experience. Constructing and testing the crane allowed students to better understand how design elements, such as boom length and counterweight placement, influence stability and overall performance.

Through analyzing individual student reflections, it became evident that constructing and testing the crane enhanced students' understanding of how design decisions, such as boom length and counterweight placement, influenced the crane's stability. However, grading of the reports and presentations highlighted significant challenges in accurately drawing free-body diagrams (FBDs) and performing the correct equilibrium analyses of both external and internal forces. This highlighted a need for a more targeted learning tool to bridge the gap between theoretical understanding and practical application.

To address these deficiencies and evaluate the potential impact of immersive learning, it was decided that the VR game to be developed should focus on improving students' ability to create accurate FBDs and calculate internal forces within trusses (the boom of the crane can be simplified as a truss). The game will incorporate the two main methods of truss analysis: the method of joints and the method of sections. Below are snapshots of the environment and assets created by the undergraduate students. The idea is for the VR games to start similar to any game where there are options to know more about the game through pressing "About", or click on "Help" to know how to navigate throughout the game (Figure 1a). The user may also select different game "levels" that will depend on their mastery of the topic (Figure 1b). To start a higher level, the user will be prompted to complete a short quiz to demonstrate that they have the basic knowledge required to "skip" the current level and move to a higher one.

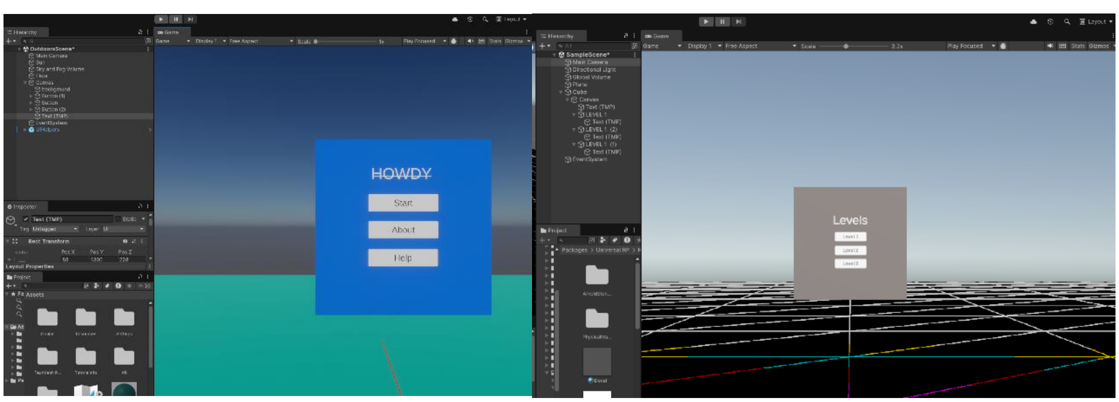

Figure 1 (a) left – An screenshot showing the Welcome screen on the VR game, (b) right – An screenshot of the different game levels that the users may interact with

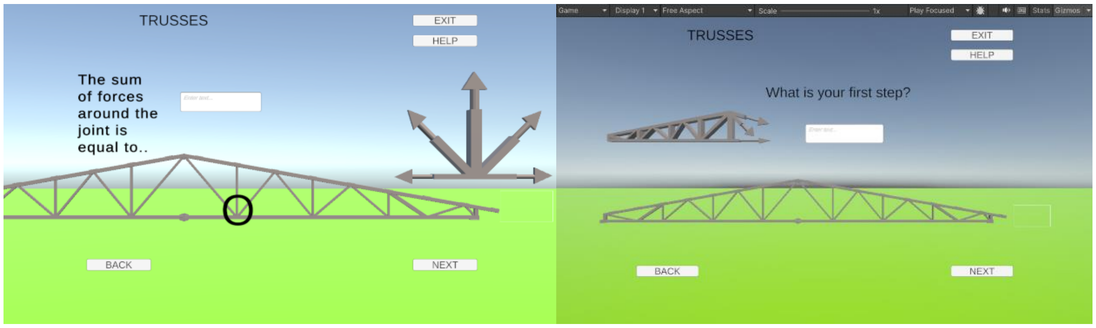

Figure 2 (a) left – A screenshot of the VR game guiding the user through the method of joints, (b) right – A screenshot of the game guiding the user through the method of sections for truss analysis

Figure 2 shows preliminary environment and asset creation of the two methods of truss analysis where in both methods, the user sees the full truss as well as the free body diagram of the joint (Figure 2 (a) or the section (Figure 2(b)) depending on which method the user chooses to determine the internal forces within the truss members.

Further work is needed to complete the different phases of the VR game mentioned above in the expectation that students will be able to further interact with the assets through application of external loads or moments and seeing the effect of changes in loading conditions on the stability of the stress. The students will be able to isolate members, joints, make sections and see how external loads will affect the internal loads within the truss members and therefore affecting its stability.

VIII. Assessing the VR experience

Based on research by Ghazali et al. [11], students reported consistently higher comprehension and motivation after VR sessions. Surveys were used to record students' views on whether VR could keep them interested, with high percentages strongly agreeing that VR sessions excited them and made learning more engaging. In addition, surveys done after sessions by Halabi [12]comparing conventional approaches to VR-based learning showed higher rates of enthusiasm, better learning perceptions, and more motivation for students who learned using VR.

Based on reviewed literature and established practices, recommended survey items include:

- "The VR activities enhanced my understanding of the subject matter."
- "The VR-based learning increased my motivation and enthusiasm for the subject."
- "I feel more engaged during VR learning sessions compared to traditional classes."
- "Using VR improved my ability to retain and recall course material."
- "I experienced discomfort or technical issues (e.g., motion sickness, graphics quality) during the VR sessions."
- "Overall, I am satisfied with my VR learning experience (rated on a scale of 1–10)."

In addition to surveys and statistical analysis, practical skill assessment is crucial to confirming the efficacy of VR learning spaces:

a. *Conceptual Quizzes (Pre/Post Testing):* Assess student understanding prior to and after VR sessions to measure instant learning effect.

b. *Practical Performance Exercises:* Spatial reconstructions test students' capability to use learned VR-related abilities in practice.

These methods have proved that those learning with VR consistently perform at least as well as, or better than, traditionally trained counterparts, validating VR's use in enabling richer learning and functional skill acquisition [13], [14]. To maximize the educational impact of virtual reality (VR), instructors and developers should implement clearly defined learning objectives within VR modules to guide student engagement and outcomes. They should also introduce systematic and routine feedback mechanisms, such as surveys and skill assessments, to continuously evaluate student understanding and experience. Additionally, applying robust statistical methods is essential for tracking and analyzing student performance over time, ensuring that the effectiveness of the VR interventions can be measured and refined for future improvement.

IX. Suggested Survey Questions

Please rate your agreement with each statement using the following scale:

***These questions were formatted and formulated with the help of ChatGPT:**

- **1** - Strongly Disagree
- **2** - Disagree
- **3** - Neutral
- **4** - Agree
- **5** - Strongly Agree

A. Learning and Understanding

1. The VR activities enhanced my understanding of complex mechanical concepts.
2. VR helped me visualize engineering problems better than traditional methods.
3. I could effectively apply concepts learned through VR to solve engineering problems.

B. Engagement and Motivation

4. I felt more engaged during VR sessions compared to standard lectures.
5. The VR activities increased my motivation to learn more about the subject.
6. I found the VR learning experience exciting and stimulating.

C. Retention and Recall

7. I believe the concepts learned through VR will be easier for me to remember over time.
8. VR experiences improved my ability to retain complex engineering information.

D. Practical Skills and Application

9. VR allowed me to safely practice engineering tasks that are typically risky or costly.
10. The VR simulations improved my confidence in performing practical engineering tasks.

E. Technical Experience

11. The VR graphics and visuals were clear and effectively represented real engineering scenarios.
12. I experienced minimal technical issues (e.g., graphics glitches, motion sickness) during the VR sessions.
13. The VR hardware (e.g., headset, controllers) was comfortable and easy to use.

F. Overall Experience and Future Use

14. I am satisfied with the overall VR learning experience.
15. I prefer VR-based learning methods over traditional classroom methods.
16. I recommend incorporating VR into more engineering courses.

Open-Ended Questions:

17. What did you find most beneficial about the VR learning experience?
18. What challenges or difficulties did you encounter during the VR sessions?
19. What suggestions do you have to improve the VR experience?

X. Conclusions

VR environments and gamifying education presents an advanced and adaptive tool for enhancing student engagement and retention. The current VR game represents an engaging approach to teaching engineering mechanics statics, offering clear learning outcomes that enhance students' understanding of rigid bodies, while enhancing both the spatial and technical awareness of forces in 3D spaces. By integrating the game into the course curriculum, the student engagement extends beyond the classroom and textbook environment and rather encourage and foster a diverse learning environment. The current approach provides an interactive and expandable platform that complements traditional teaching methods, fostering stronger spatial reasoning skills, better problem-solving abilities, and increased confidence in applying statics principles to real-world engineering challenges.

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