Integrating Virtual Reality into engineering education: An interactive application for learning mechanisms

Petru-Iulian GRIGORE, Corneliu Octavian TURCU

Faculty of Electrical Engineering and Computer Science,
"Stefan cel Mare" University of Suceava, Romania

contact@iuliangrigore.ro, cturcu@usm.ro

Abstract: *This study presents a VR-based educational application designed to enhance students' understanding of mechanical systems, focusing on crank-slider mechanisms, oscillating slides, crank-piston systems, and four-bar linkages. The application integrates 3D models, animations, and interactive simulations, aligning with Bloom's Taxonomy to facilitate progressive cognitive development. A Virtual Instructor Drone provides AI-guided explanations, ensuring structured learning, while the Introductory Scenario familiarizes students with VR navigation and object manipulation. Students participate in piston assembly, engine integration, and dynamic motion demonstrations, reinforcing spatial awareness and practical skills. The FreeRoom Scenario promotes independent exploration, problem-solving, and creative thinking. Findings indicate that VR enhances engagement (28%), interactivity (26%), and visualization (16%). However, challenges such as initial adaptation difficulties (30%) and spatial orientation issues (9%) suggest the need for improved onboarding and navigation support. Future research will evaluate knowledge retention and skill acquisition through pre- and post-evaluation studies, using surveys and focus groups. By combining structured learning, hands-on interactivity, and real-time feedback, this VR-based approach effectively bridges theory and practice, providing an innovative solution for engineering education*.

Keywords: Virtual Reality, Engineering Education, Crank-Slider Mechanism, Interactive Learning.

1. Introduction

Virtual Reality (VR) has become a key technology in education, providing immersive, interactive learning experiences that significantly enhance student engagement and comprehension (Grigore & Turcu, 2024). Recent research has examined the integration of VR across various educational fields, including engineering, biology, and general pedagogy, emphasizing its potential to revolutionize conventional instructional approaches.

Engineering education integrates both theoretical foundations and hands-on applications. Traditional methods textbooks, 2D diagrams, and physical models

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often fail to effectively convey the complexity of mechanical systems, hindering students' ability to grasp and visualize key concepts. Virtual Reality mitigates these challenges through immersive simulations, bridging the gap between theory and practice. This enables students to actively engage with and explore complex systems in a dynamic learning environment (Grigore & Turcu, 2024).

This paper presents a VR-based educational application centered on the crank-slider mechanism, a fundamental component in engines and industrial machinery. Mastering this mechanism is essential for mechanical engineering students. The VR application enables users to interact with it, observe its motion dynamics, and conduct virtual experiments in a controlled, risk-free setting. This study aims to outline the development process of the VR tool and examine its potential applications in engineering education. Furthermore, the application aligns with Bloom's Taxonomy, supporting a structured learning progression from foundational knowledge acquisition to the development of advanced cognitive skills.

2. Literature review

Virtual Reality in education is rooted in theories emphasizing experiential learning and active engagement. Abbas Shah et al. (2024) and Grigore & Turcu (2024) argue that incorporating educational frameworks into VR-based laboratories enhances learning outcomes by providing immersive experiences that foster knowledge construction and personalized learning. Their analysis underscores the importance of aligning VR applications with established pedagogical models to optimize their educational impact. Similarly, Morimoto & Ponton (2021) suggest that VR revitalizes naturalistic teaching methods by enabling students to actively explore biological concepts in virtual environments, enhancing their observational and analytical skills.

Research has examined Virtual Reality's role in engineering education, emphasizing its effectiveness in simulating complex real-world scenarios. Han (2023) notes that traditional teaching methods often struggle to convey abstract engineering concepts, whereas VR provides a more intuitive and interactive learning experience. Similarly, Halabi (2020) supports this view, showing that integrating VR with project-based learning enhances students' problem-solving skills and fosters teamwork. Their study found that students engaged in VR-based engineering design projects demonstrated superior conceptual understanding and practical application compared to those using conventional methods.

Abulrub, Attridge & Williams (2011) highlight VR's potential to foster creativity and innovation in engineering education. Their study suggests that VR-based simulations enable students to explore and visualize engineering concepts in a controlled virtual environment, enhancing spatial awareness and technical skills. Similarly, the growing adoption of VR in engineering education is driven by its effectiveness in bridging theoretical learning and real-world applications, as noted in Virtual Reality in Engineering Education (2011).

Beyond engineering, VR is increasingly recognized as a valuable tool in science education. Morimoto & Ponton (2021) highlight VR’s role in evolutionary biology, where virtual field trips and simulated ecosystems provide students with unprecedented opportunities to engage with biological phenomena. Their study underscores VR’s capacity to enhance traditional fieldwork by providing controlled, interactive environments for examining ecological and evolutionary processes. Nasrullah et al. (2024) further highlight the growing role of VR in education through a bibliometric analysis, revealing a significant increase in scholarly interest over the past decade. Their findings suggest that VR is increasingly regarded as a viable alternative to traditional multimedia learning tools, particularly in STEM education.

Despite VR's well-documented benefits in education, several challenges impede its widespread adoption. Criollo-C et al. (2024) identify cost, accessibility, and technological limitations as major obstacles to implementation. Although VR hardware costs are declining, many educational institutions continue to face financial constraints and limited technical expertise, hindering effective curriculum integration. Grigore & Turcu (2024) suggest that familiarity with online platforms moderately influences students' perceptions of VR as a beneficial learning tool, indicating that prior digital engagement facilitates VR's integration into education.

A key challenge is developing VR content that aligns with pedagogical objectives. Halabi (2020) underscores that while VR can enhance learning outcomes, its effectiveness hinges on instructional design quality and its ability to engage students in meaningful learning experiences. Similarly, Abbas Shah et al. (2024) emphasize the need to anchor VR-based learning environments in sound educational principles to maximize impact and achieve learning objectives.

3. Methodology and technologies used

This section details the development of a VR application aimed at providing an interactive and immersive learning experience. The application familiarizes students with VR technology while teaching the crank-slider mechanism, a core engineering concept. The development followed a structured approach to ensure educational accuracy and pedagogical relevance. The key pre-development phases included the following:

1. Collaboration with the Supervising Professor: An academic expert oversaw the project, defining educational objectives and emphasizing VR's significance in engineering education. The crank-slider mechanism was selected as the focal topic for its relevance and educational value.

2. Research on the Crank-Slider Mechanism: Consultations with the professor ensured the accuracy of the educational content. Key information gathered included: Theoretical principles of the mechanism; Main components and their functions; Practical engineering applications; Animations developed using Linkage software.

3. Design and Evaluation of Learning Scenarios: Various scenarios were developed, from basic simulations to complex interactive experiences. These scenarios were evaluated based on: Pedagogical relevance; Interactivity level to enhance engagement; Practical application of theoretical knowledge.

4. Defining Application Objectives: Educational goals were clearly defined to uphold academic rigor. The objectives included: Interactive teaching of the crank-slider mechanism; Providing a safe environment for experimentation; Enhancing student motivation and engagement through immersive learning.

3.1 Application development

This VR application provides students with an interactive and practical approach to understanding the crank-slider mechanism in a safe virtual environment. Developed for Meta Quest 2, it incorporates structured educational scenarios, immersive interactions, and hands-on activities to reinforce theoretical learning:

- VR Familiarization: An interactive tutorial introduces students to Meta Quest 2, guiding them through fundamental interactions;
- Immersive Learning Environment: The app integrates visual, auditory, and interactive elements to foster an engaging and dynamic experience;
- Structured Educational Scenarios: Content is systematically structured to enhance accessibility and comprehension;
- Practical Skill Development: Interactive exercises, such as assembly and analysis, allow students to apply theoretical knowledge in a hands-on setting;

Developed using Epic Games' VR template, the app integrates customized mechanics, such as object manipulation, to enhance interactivity. Existing functionalities were adapted to align with educational objectives, ensuring seamless integration of interactivity and pedagogy. The VR scene was carefully designed to balance immersion and usability. Its layout maximizes space for interaction while preserving visual clarity. Performance factors, such as scene scale and graphics quality, were prioritized to ensure smooth operation on Meta Quest 2.

3.2 Virtual instructor

A virtual drone serves as an instructional guide, enhancing engagement and interactivity in the VR learning environment. This AI-driven assistant provides real-time guidance, explanations, and visual support, fostering a structured and immersive educational experience.

Key Features and Functionalities:

- Audio Instructions: AI-generated voice guidance with synchronized subtitles improves accessibility;
- Integration in the educational scenario: The drone actively explains technical concepts, such as the crank-slider mechanism, reinforcing comprehension;
- Visual Support: A virtual screen strategically displays relevant data alongside verbal explanations;
- Interactive Guidance: Step-by-step assistance in practical exercises enhances learning efficiency and hands-on application.

A key feature of the drone is its dynamic student interaction capability. The drone continuously tracks the student's position, maintaining proximity throughout the lesson to ensure ongoing support. Using the FacePlayer function, the drone dynamically adjusts its orientation with FindLookAtRotation and SetWorldRotation, ensuring it consistently faces the student for an intuitive and responsive learning experience. The drone navigates to predefined locations, structuring the lesson flow and guiding students through key educational points in the VR environment. This feature improves lesson organization while maintaining student engagement and focus on educational content.

Additionally, Unreal Engine 5 audio assets natively support subtitles, ensuring precise synchronization between spoken instructions and on-screen text. By integrating AI-driven guidance, dynamic movement, and structured interactivity, the drone functions as a key facilitator in VR-based learning, enhancing student engagement and comprehension.

3.3 Introductory scenario

The introductory scenario facilitates students' transition into VR learning, reducing barriers and building confidence in using VR equipment. This stage establishes a structured and engaging foundation, ensuring accessibility and a smooth progression to advanced educational modules. The drone-based virtual instructor is essential for student orientation. Through dynamic positioning, auditory guidance, and synchronized subtitles, it: Directs user attention to relevant 3D objects; Provides step-by-step instructions for VR interactions; Enhances engagement by acting as both an information source and interactive element.

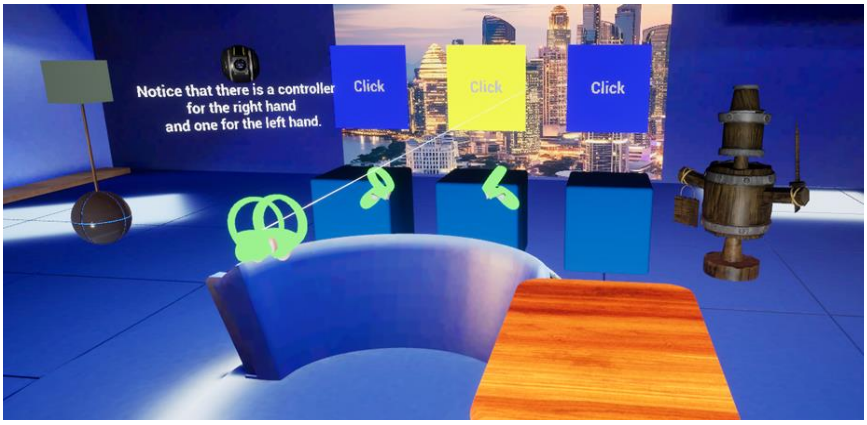

Figure 1. Introductory scenario

This scenario (Figure 1) familiarizes students with the VR environment and controllers, facilitating a smooth transition to more advanced educational tasks. It introduces core interactive activities that cultivate essential VR navigation and interaction skills. A key activity, object manipulation and selection, enables students to engage in hands-on interactions, learning to effectively use VR controllers for selecting and handling virtual objects. Additionally, Navigation and Movement training instructs students on traversing the VR environment using controller inputs, reinforcing spatial awareness and control.

To enhance mobility and reduce motion sickness, the scenario incorporates teleportation, enabling seamless movement between locations in the VR space. This feature enhances comfort and accessibility, particularly for users unfamiliar with virtual reality navigation. Students develop perspective control, adjusting their viewpoint naturally by rotating their head or using controller inputs for precise modifications. Additionally, object interaction and action triggers refine motor skills by instructing students on grasping, moving, and manipulating objects to activate mechanisms or complete specific tasks.

A key component of this scenario is controller familiarization, providing a structured introduction to VR controller functions. Visual and auditory cues provide step-by-step guidance, reinforcing students' understanding of VR interactions. This introductory phase employs a progressive learning approach, ensuring students develop confidence and competence before progressing to advanced educational tasks. Structured activities and interactive guidance maximize engagement and comprehension, significantly enhancing the VR learning experience.

3.4 Educational scenario

After the introductory phase, the educational scenario becomes the core of the VR system, providing an interactive and engaging learning experience. It deepens students' understanding of the crank-slider mechanism and related systems, allowing them to apply theoretical concepts in a virtual hands-on setting. The VR-based application incorporates detailed 3D models and animations to support exploration of crank-slider mechanisms, double oscillating slides, crank-piston systems, and four-bar linkages. Animations and interactive elements offer clear visualizations of mechanical operations, making complex concepts more accessible and intuitive.

Students engage in hands-on interactivity, manipulating 3D components in real time. This feature reinforces practical mechanical insights while deepening students' understanding of mechanical systems. Additionally, visual aids, including informative images and animations, are displayed on a virtual screen to enhance concept retention and comprehension. Multiple-choice tests assess students' grasp of key concepts before progressing to advanced topics. These assessments evaluate comprehension and reinforce foundational knowledge, ensuring a structured learning progression.

Figure 2. Educational scenario

During the Piston Assembly & Engine Integration phase (Figure 3), students assemble a piston and integrate it into a virtual engine using VR controllers. This hands-on experience improves spatial awareness and mechanical precision, equipping students for real-world applications. Real-time visual and auditory feedback confirms correct actions and sustains engagement throughout the learning process. This reinforcement enhances retention and builds student confidence. Finally, an animated engine simulation illustrates how piston movements produce rotational motion, reinforcing students' understanding of mechanical transformations.

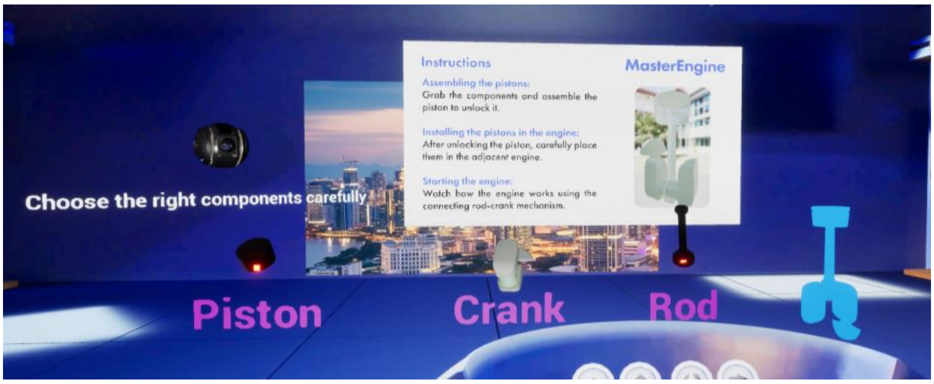

Figure 3. Piston assembly task

This VR-based educational scenario provides an interactive and immersive learning experience in engineering. By integrating structured guidance, hands-on engagement, and real-world applications, it effectively bridges theory and practice. VR technology enhances comprehension, retention, and skill development, establishing it as a valuable tool in modern engineering education.

3.5 Integration with Bloom's Taxonomy

VR educational scenarios are structured in alignment with Bloom's Taxonomy to ensure an effective learning experience. This framework classifies cognitive learning into six hierarchical levels. The application systematically covers each domain, as detailed in the following breakdown:

- Remember (Knowledge Acquisition): The educational scenario presents fundamental engineering concepts using structured explanations, animations, and real-time 3D visualizations. The Virtual Instructor Drone reinforces learning through AI-generated voice instructions and synchronized subtitles, guiding students step by step;
- Understand (Conceptual Comprehension): Dynamic simulations enable students to explore mechanical interactions and visualize component relationships. The Knowledge Testing for Advancement phase reinforces conceptual retention through interactive quizzes with real-time feedback;
- Apply (Practical Implementation): Comparative analysis in the educational scenario enables students to differentiate between crank-slider and similar mechanisms. The FreeRoom scenario supports independent exploration, guiding users in identifying key functional differences between mechanical structures;
- Analyze (Comparative and Structural Understanding): The educational scenario enables students to conduct a comparative analysis, differentiating crank-slider from similar mechanisms;

- Evaluate (Critical Thinking and Decision-Making): The knowledge testing for advancement phase promotes self-assessment and critical thinking before progression;
- Create (Synthesis and Innovation): The VR application fosters creativity by enabling students to reconstruct mechanical assemblies and explore new configurations.

4. Results

This section examines student feedback on VR technology in education, based on responses from 43 participants who completed the VR scenarios. Table 1 presents the response rate and abstentions, providing an overview of participant engagement and the dataset used in this analysis.

Table 1. Response rate and abstentions

Question	Responses	Abstentions
1 The best aspects	33 (77%)	10 (23%)
2 The most difficult aspects	19 (44%)	24 (56%)
3 Suggestions for improvements	24 (56%)	19 (44%)

1. Best aspects of using VR in learning

Students highlighted key benefits of VR technology in education. Thematic analysis of responses (Table 2) identifies four key themes: attention capture, interactivity, realism and visualization, and concept clarification.

Table 2. Thematic analysis of feedback on positive aspects

Theme	Frequency	%	Example responses
Capturing attention	12	28%	"Maintaining attention and interest was much easier."
Interactivity	11	26%	"Direct interaction with various mechanisms is great."
Realism and visualization	7	16%	"The experience was realistic, and the clear visuals clarified my ideas."
Clarifying concepts	3	7%	"Visualizing technical concepts helped me understand better."

The most frequently cited benefit (28% of students) was VR's capacity to capture and sustain attention. Students reported that VR made lessons more engaging and dynamic, helping them maintain focus throughout the learning experience. Additionally, 26% of participants cited interactivity as a key strength, noting that direct engagement with mechanical systems and hands-on simulations improved their learning.

VR’s realism and high-quality visualizations (16% of respondents) were seen as crucial for enhancing understanding, providing clear and tangible representations of theoretical concepts. Although cited by only 7% of students, VR’s ability to clarify complex technical ideas was considered a significant advantage, with direct visualizations aiding comprehension.

2. Challenges in using VR for learning

Although students recognized VR’s benefits, they also identified challenges (Table 3). The most frequently cited challenge (30% of participants) was the initial adaptation phase. Many students found the first 3–5 minutes of VR use particularly challenging as they familiarized themselves with the controls and interface. This highlights the need for enhanced onboarding tutorials to ease the learning curve.

Table 3. Thematic analysis of feedback on difficult issues

Theme	Frequency	%	Example responses
Initial Adaptation	13	30%	"The first 3-5 minutes of use are more difficult until you adapt."
Spatial Orientation	4	9%	"Lack of attention to space and risks in confined space."
Technical Issues	2	5%	"Sometimes it freezes."

The second most reported challenge (9% of students) was spatial orientation. Some participants reported difficulties in maintaining awareness of their physical surroundings, particularly in confined spaces. These findings underscore the need for safety guidelines and virtual boundaries to prevent unintended movement or collisions. Less commonly, 5% of students experienced technical issues, including occasional software freezing, which disrupted their learning experience.

3. Suggestions for improving the VR learning experience

Students offered suggestions to enhance VR-based learning (Table 4). The most frequently suggested improvements focused on technology optimization and expanding educational scenarios, each cited by 19% of respondents.

Table 4. Thematic analysis of feedback on improving the VR experience

Theme	Frequency	%	Example responses
Technology Optimization	8	19%	"Better resolution for understanding the text."
Additional Scenarios	8	19%	"More lessons and educational scenarios should be developed."
No Changes	6	14%	"I wouldn’t change anything; the interaction was immediate, and I look forward to more experiences like this."
More Intuitive Controls	2	5%	"I would adopt glove-based controls."

For technical improvements, students requested higher resolution for clearer text and visuals, highlighting the role of display quality in information retention. Additionally, participants suggested diversifying educational scenarios, noting that an expanded curriculum could enhance VR learning’s versatility and applicability. Notably, 14% of students expressed satisfaction with the current implementation, stating that no major changes were necessary. This positive feedback reinforces the effectiveness of the interactive design. However, 5% of students proposed more intuitive control systems, such as glove-based interactions, to improve usability and ergonomics.

Students' feedback highlights both the strengths and challenges of using VR technology in education. Key benefits include enhanced engagement, interactivity, and improved visualization of complex concepts, whereas initial adaptation, spatial awareness, and technical stability require improvement.

5. Conclusions and future work

This study examines the educational impact of a VR-based learning environment aligned with Bloom’s Taxonomy, aimed at enhancing engagement, knowledge retention, and skill development. Although formal testing is pending, student feedback emphasizes the application’s immersive and interactive nature, noting its superiority over traditional teaching methods.

Key benefits identified include:

- Engagement: 28% of students praised VR’s capacity to sustain attention, making lessons more dynamic;
- Interactivity: 26% of students highlighted that direct interaction with mechanical systems enhanced understanding;
- Visualization: 16% of students noted that realistic 3D representations improved the clarity of complex engineering concepts.

In addition to engagement, knowledge retention emerged as a key outcome. The application’s multi-sensory learning approach, integrating visual, auditory, and kinesthetic elements, effectively reinforced engineering principles. Structured animations and interactive tutorials delivered clear explanations, fostering deeper and more enduring comprehension. However, 9% of students reported spatial orientation difficulties, highlighting the need for improved navigation guidance and safety features.

For practical skill development, the Piston Assembly and Engine Completion phase offered hands-on experience, enabling students to manipulate mechanical components and apply theoretical knowledge in a realistic setting. The FreeRoom Scenario promoted independent exploration and problem-solving, which students valued for fostering analytical thinking and design innovation. Although uncommon, 5% of students reported occasional technical issues, including software freezing, indicating a need for system stability optimization to improve the learning experience.

This study’s findings align with prior research on VR’s benefits in education, reinforcing the advantages of immersive learning environments. The results show that students perceived VR-based learning as more engaging and interactive than traditional methods, aligning with Han (2023) and Halabi (2020), who highlighted VR’s role in enhancing student motivation and conceptual understanding. While Criollo-C et al. (2024) identified cost and accessibility as primary barriers to VR adoption, this study introduces empirical feedback through thematic analysis and emphasizes user-experience limitations that can be mitigated through design improvements.

Although this VR-based educational application shows strong potential in engineering education, further research is needed to assess its effectiveness and impact. Future research will involve quantitative assessments of knowledge gain, task performance, and interaction efficiency, as well as qualitative studies on usability, engagement, and perceived learning benefits.

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