





Enhancing stem learning through augmented reality: Applications in CAD and Mechanical systems





Mejora del aprendizaje de los tallos mediante la realidad aumentada: Aplicaciones en CAD y sistemas mecánicos

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SECIHTI classification:

Área: Engineering
Campo: Engineering
Disciplina: Industrial Engineer
Subdisciplina: Technological Innovation

 <https://doi.org/10.35429/JIE.2025.9.21.7.1.11>

Article History:

Received: September 25, 2025

Accepted: December 10, 2025

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Abstract

This study presents the development of immersive applications using augmented reality (AR) technologies to enhance the teaching and learning process of computer-aided design (CAD) and mechanism simulation in the engineering education program. The research focuses on increasing student engagement, improving spatial understanding, and providing blueprint manufacturing interpretation. AR tools were designed and implemented in university-level courses, with an emphasis on interactivity, technical precision, and real-time feedback. Results indicate significant improvements in spatial reasoning, blueprints interpretation, and assembly's manipulation, confirming the value of immersive learning environments in science, technology, engineering and mathematics (STEM) education.



Augmented Reality, Computer-Aided Design, Mechanism Simulation, STEM Education, Immersive Learning

Resumen

Este estudio presenta el desarrollo de aplicaciones inmersivas utilizando tecnologías de realidad aumentada (AR) para mejorar el proceso de enseñanza y aprendizaje del diseño asistido por computadora (CAD) y la simulación de mecanismos en la educación en ingeniería. La investigación se enfoca en mejorar la comprensión espacial y la interpretación de planos de manufactura. Las herramientas de AR fueron diseñadas e implementadas en cursos a nivel universitario, con énfasis en la interactividad, la precisión técnica y la retroalimentación en tiempo real. Los resultados indican mejoras significativas el razonamiento espacial, interpretación de planos y la manipulación de ensambles, lo que confirma el aprendizaje inmersivo en la educación, ciencia, tecnología, ingeniería y matemáticas (STEM).



Realidad aumentada, diseño asistido por computadora, simulación de mecanismos, educación STEM, aprendizaje inmersivo

Area: Development of strategic leading-edge technologies and open innovation for social transformation

Citation: Meraz-Mendez, Manuel, Corral- Ramirez, Guadalupe, Muñoz-Lopez, Luis Enrique and Duarte-Loera, Jorge. [2025]. Enhancing stem learning through augmented reality: Applications in CAD and Mechanical systems. Journal Industrial Engineering. 9[21] 1-11: e70921111.



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Introduction

Engineering students often face challenges when transitioning from theoretical knowledge to applied design and mechanism simulation. Traditional CAD instruction relies on 2D interfaces and screen-based interactions, which may limit students' spatial reasoning and understanding of mechanical motion (Adurangba et al., 2023; S. -M. Wang et al., 2024). Similarly, interpreting mechanical systems behavior from static diagrams or simplified animations often lacks the immersive depth required for full comprehension (Li et al., 2020; Ka, J. et al., 2025)

To address these limitations, this research proposes the development of AR applications that transform the way students interact with CAD models and mechanical systems. These tools aim to enhance learning outcomes, improve conceptual visualization, and foster active, self-directed learning in safe, repeatable virtual environments (Akçayır & Akçayır, 2022; Meraz & Reynoso, 2022; Makransky & Petersen, 2021).

Background

The advancement of engineering education in the context of Industry 4.0 demands pedagogical strategies that integrate emerging technologies capable of enhancing students' spatial reasoning, system-level understanding, and hands-on technical skills. Among these technologies, AR and virtual reality (VR) have gained attention as transformative tools that enable immersive, interactive, and student-centered learning environments—particularly in domains such as CAD and mechanical systems (Li et al., 2020; Akçayır & Akçayır, 2022).

AR enriches the physical environment with digital content, allowing students to visualize 3D models overlaid on real-world objects, while VR enables full immersion in simulated environments where learners can interact with mechanical systems without the constraints of physical equipment (Radianti et al., 2020). These capabilities have proven valuable in supporting spatial understanding, procedural learning, and safe experimentation (Bower et al., 2020; Nasija et al., 2024).

Spatial reasoning is widely recognized as a critical skill for success in engineering education, especially in early design and mechanical systems courses (S. -M. Wang et al., 2024). However, traditional tools—such as orthographic drawings, 2D diagrams, and static physical models—often fall short in helping students internalize complex 3D relationships and dynamic motion. As a result, many students struggle with interpreting CAD representations, assembling mechanical systems, and predicting kinematic behavior (Ka, J. et al 2025).

Studies have shown that AR and VR can mitigate these challenges by offering real-time manipulation of 3D models, simulated animations, and guided interaction, which lead to better conceptual understanding and higher student motivation (Ferrer-Torregrosa et al., 2020; Salgado F. et al., 2022). In particular, immersive learning environments encourage active exploration and experiential learning, both of which are linked to deeper cognitive engagement and improved knowledge retention (Makransky & Petersen, 2021).

Despite promising results, many implementations of AR/VR in engineering remain isolated or exploratory, lacking robust integration into the instructional design process or formal assessment of their educational impact (Adurangba V. et al., 2023). This project aims to address that gap by developing a series of targeted AR and VR applications embedded into CAD and mechanical simulation curricula, designed to align with learning outcomes and rigorously evaluated for effectiveness in improving student performance and engagement.

Methodology

This study adopts a design-based research (DBR) approach to the development and evaluation of AR applications in the context of STEM education. The goal is to enhance the teaching and learning process of CAD and mechanism systems simulation in the maintenance engineering and mechanical education programs particularly focusing on improving spatial visualization, conceptual understanding, and student engagement.

The methodology shown in Figure 1 consists of five integrated stages: (1) curriculum analysis, (2) system design, (3) development and implementation, (4) instructional deployment, and (5) evaluation.

Box 1

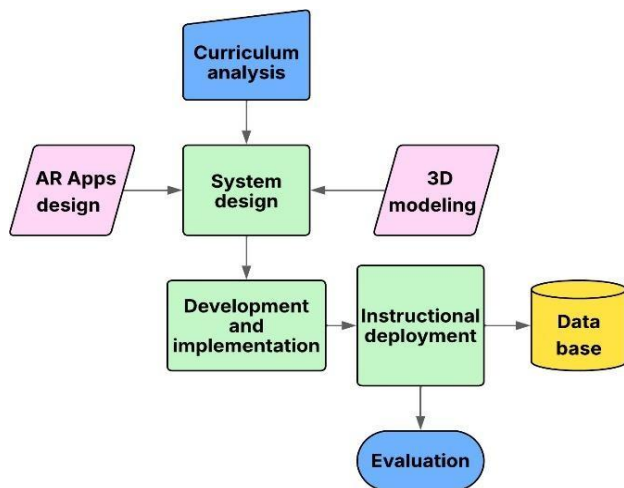


Figure 1

Methodology for AR environments implementations in STEM education

Curriculum and Needs Analysis

The first stage involved a thorough analysis of the curriculum of two undergraduate engineering courses: “Computer-Aided Design” and “Mechanical systems.” A gap analysis was conducted through interviews with instructors, direct observation of student challenges during practical sessions, and examination of previous student performance data. Particular attention was given to read and interpret mechanical drawings that presented cognitive and spatial difficulties, such as interpreting orthographic projections, manufacturing symbols, and visualizing component assemblies. These findings informed the selection of learning objectives to be enhanced through AR.

In parallel, a technology readiness assessment was conducted to evaluate the availability and suitability of existing hardware (AR headsets, AR-enabled tablets) and software platforms (Unity, Unreal Engine, SolidWorks) within the university's infrastructure.

System and Content Design

The instructional design process was guided by principles of STEM education focused in the immersive learning, emphasizing active exploration, manipulation, and visualization.

ISSN: 2523-0344

RENIECYT-SECIHTI: 1702902

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Learning Scenarios: Scenarios were analyzed to solve specific learning problems:

- Learning problems in interpreting drawings and manufacturing symbols in blue prints (Figure 2).
- Learning problems in visualization of exploded views and part relationships in CAD assemblies (Figure 3).
- Learning problems in training assemblies' operations (Figure 4).

Box 2

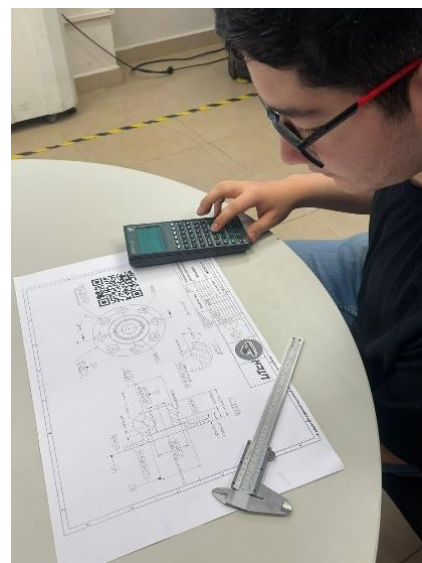


Figure 2

Student trying to interpret manufacturing symbols

Box 3

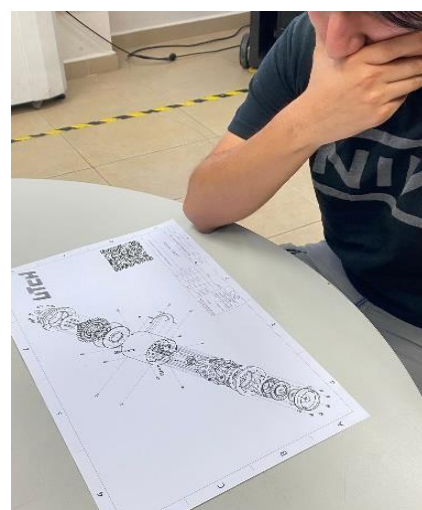


Figure 3

Student trying to interpret explode views in assemblies

Box 4

Figure 4
Student trying to resolve mechanical assemblies

Design Criteria

To address these problems, AR-Apps were designed to meet the following criteria:

- Pedagogical alignment: Directly support course outcomes and assessment criteria.
- Interactivity: Enable real-time manipulation of 3D models or simulation parameters.
- User-friendly interface: Accessible to students with minimal training.
- Technical accuracy: Models and simulations must reflect engineering standards and behaviors.

Storyboards, wireframes, and mockups were iteratively developed and reviewed by instructors and student focus groups to ensure usability and pedagogical value.

AR Applications Development and Integration

To develop the AR apps industry-standard tools were used:

3D Modeling: SolidWorks was used to design CAD models of mechanical systems (e.g., gear trains, cams, linkages), as shown in Figure 5. These models were then exported in Collada format.

AR Application: Unity 3D with the Vuforia SDK was used to develop marker-based and spatial AR applications, which were deployed on Android tablets.

Unreal Engine was used to build immersive environments, interactive simulations, and user-controlled interfaces compatible with MetaQuest, as shown in Figure 6.

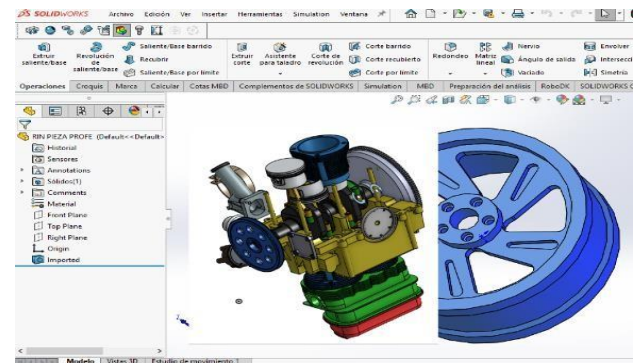
Box 5

Figure 5
SolidWorks modeling

Box 6

Figure 6
AR Apps design

Specific features included:

AR-Apps overlay of exploded views and technical annotations on physical printouts and lab equipment, as shown in Figure 7.

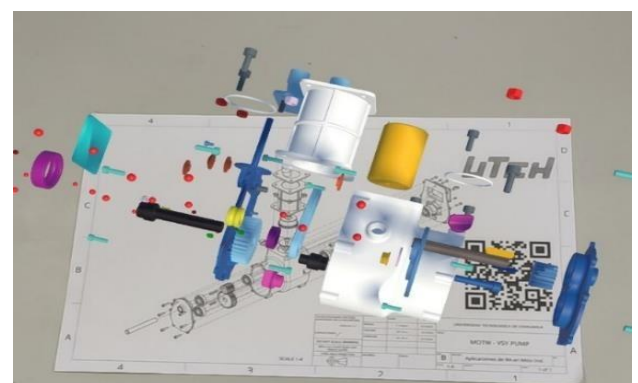
Box 7

Figure 7
AR-Apps for assemblies exploded views

AR-Apps based in interactive mechanism labs with assembly comprehension, as shown on Figure 8.

Box 8

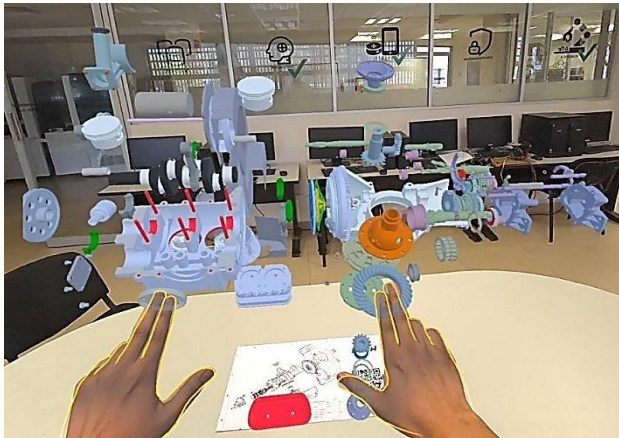


Figure 8

AR-Apps for assembly comprehension

Virtual assembly trainers, allowing students to practice positioning and constraining components in mechanical systems using virtual tools as shown in Figure 9.

Box 9

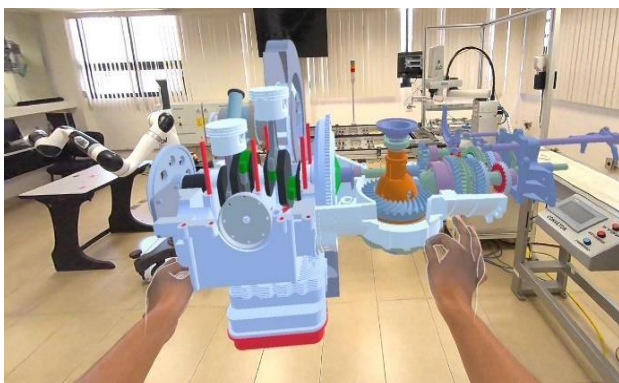


Figure 9

AR-Apps for assembly positioning and constraining components

AR-Apps based in interpretation of manufacturing symbols, as shown in Figure 10.

Box 10

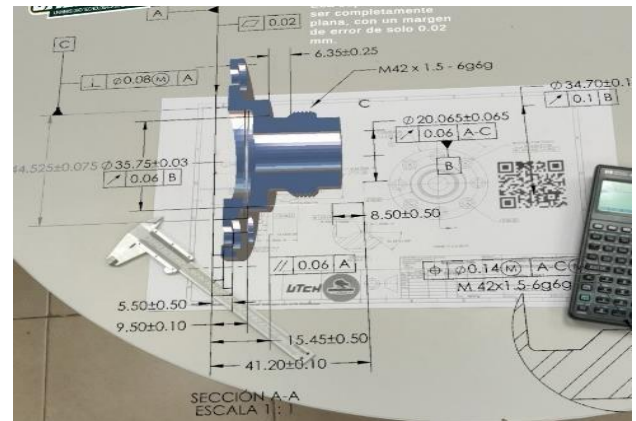


Figure 10

AR-Apps for interpreting manufacturing symbols

Cross-platform compatibility and lightweight model optimization were prioritized to ensure smooth performance on consumer-grade hardware. Additionally, learning analytics and user interaction logging were integrated into the backend to support post-deployment analysis.

Instructional Deployment

The AR-Apps were implemented in two engineering education institutions: The Technological University of Chihuahua (UTCH) and the National Technologic of Mexico campus Chihuahua (ITCH), in two courses: Computer-Aided Design (CAD) and mechanical systems, both in theoretical and practical sessions.

Participants: A total of 120 students, 60 from Maintenance Engineering (UTCH) and 60 from Mechanical Engineering (ITCH), corresponding to their second and fourth semesters, participated across CAD and Mechanisms analysis using AR immersive applications.

Delivery model: AR-Apps Applications were introduced during class under instructor guidance, and made available for self-paced learning in designated AR lab spaces.

Instructor training: Faculty members received training sessions to integrate the AR-Apps tools into their lessons and to interpret usage data for formative feedback.

The AR-Apps implementation overcomes to solve STEM educational problems because it incorporates: Science (understanding of physical, optical, and spatial principles in the visualization of objects), Technology (use of AR software, programming, and mobile applications), Engineering (interpretation of technical drawings, CAD modeling, and mechanical design), and Mathematics (scaling, spatial coordinates, 3D geometry, and precise measurement for model overlay).

Evaluation and Data Collection

A mixed-methods approach was employed to evaluate the impact of the developed AR-Apps applications. Data collection methods included:

Pre- and Post-Tests: Standardized assessments were administered to measure learning gains in spatial reasoning, assembly comprehension, and mechanism analysis.

Surveys and Questionnaires: The questionnaire detailed in Table 1 was implemented to assess the development of technical competencies in AR environments in Industrial maintenance and Mechanical engineering. This instrument was designed to gather empirical evidence on the effectiveness of the AR-Apps compared to traditional instructional methods.

The questionnaire measures four key aspects for learning CAD and mechanism simulation, which are: Identification of mechanical parts, visualization of explode views in assemblies, training in assembly execution and assistance in procedures for practical activities.

Box 11

Table 1

Questionnaire: Technical Competency in AR Environments

Identification of Mechanical Parts

1. Do AR environments facilitate the understanding of geometric shapes by manipulating 3D models more effectively than reading traditional 2D blueprints?

Yes No

2. Does the use of labels on 3D models in AR environments provide a clearer understanding of information than reading traditional 2D blueprints?

Yes No

Visualization of Exploded Views in Assemblies

1. Is visualizing an assembly in AR environments clearer and more comprehensible than viewing it on a printed blueprint?

Yes No

2. Is it easier to identify assembly relationships between parts in AR environments than when identifying them on a printed blueprint?

Yes No

Training in Assembly Execution

1. Do AR applications facilitate training for executing complex mechanical assemblies?

Yes No

Focus Groups: Semi-structured group interviews were applied to 60 students from the UTCH and 60 students from the ITCH were conducted with students and instructors to gather qualitative insights into user experience, technical performance, and instructional value. Quantitative data were analyzed using ANOVA to determine the statistical significance of learning improvements.

Results

The results of the evaluation process for the AR applications were organized into three categories: (1) quantitative assessment of learning outcomes, (2) student perception and engagement, and (3) qualitative insights from instructors and focus groups.

Quantitative Assessment of Learning Outcomes

Pre- and Post-Test Performance

To assess the cognitive impact of the immersive applications, students completed concept-based tests before and after using the AR-Apps tools evaluating understanding of spatial geometry, manufacturing symbols, and component assembly logic. Table 2 presents the cognitive impact results

Box 12

Table 2

Cognitive impact results

Evaluated Aspect	Sample Question	Yes (%)
Identification of Mechanical Parts	Do AR environments improve understanding of 3D shapes vs. 2D drawings?	95.1%
	Do labels in AR 3D models offer clearer understanding than 2D drawings?	92.7%
Visualization of Exploded Views	Is it clearer to visualize an assembly in AR than in a printed drawing?	95.1%
	Is identifying part relationships easier in AR than in printed drawings?	92.7%
Training in Assembly Execution	Do AR apps help train complex mechanical assembly tasks?	95.1%
Assistance in Practical Procedures	Do AR apps present clearer step sequences than printed instructions?	92.7%

Source [Questionnaire results from UTCH-ITCH Students]

Analysis showed statistically significant improvements across all groups:

CAD Course: Students' average test scores increased from 63.4% (pre-test) to 95.1% (post-test) after using AR-Apps in interpretation of manufacturing symbols, visualizations of assemblies and exploded views.

Mechanism Course: Average scores rose from 58.2% to 92.7%, particularly in questions involving motion prediction of linkages and gear interactions.

ANOVA analysis was conducted to assess learning improvements. Table 3 shows the results for the 120 students across both learning methods: with AR-Apps and without.

Box 13

Table 3

ANOVA results

Source	SS	df	F	p-value)
Group	2134.44	3	294.61	0.000038
Residual	9.66	4		

Source [Own]

The p-value of 0.000038, indicates that there are statistically significant differences between the groups (CAD_Pre, CAD_Post, Mech_Pre, Mech_Post).

Spatial Reasoning Improvement

The Spatial Visualization Test (SVT) was administered to measure spatial cognition. Students using AR-Apps showed an average gain of 28.4%, compared to a 12.1% gain in the control group using traditional 2D learning materials.

This suggests that immersive environments contributed significantly to students' spatial comprehension, which is essential for CAD and mechanical systems.

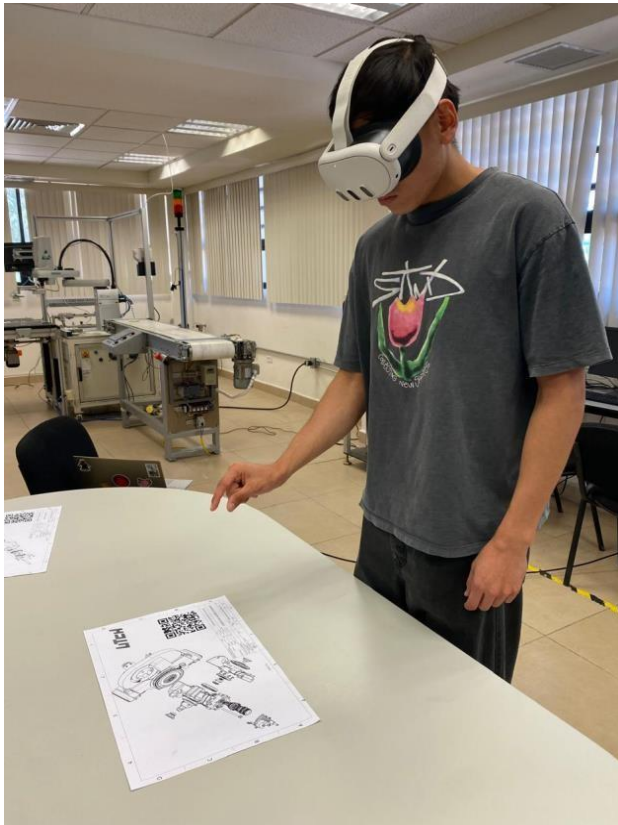
Student Perception and Engagement

Usability and Satisfaction

Post-intervention surveys using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) revealed high levels of user satisfaction:

“The AR tools helped me understand complex concepts more easily”: 4.7 average
 “I feel more confident in my CAD/mechanism skills after using the applications”: 4.5 average
 “The immersive applications were engaging and enjoyable to use”: 4.8 average

Students particularly appreciated the ability to manipulate 3D models in real time and explore mechanical motion from any angle, as this aligned closely with how real-world systems function through a MetaQuest Headset as shown in Figure 11.

Box 14**Figure 11**

Student using MetaQuest for AR

Cognitive Load and Learning Efficiency

Cognitive load was measured during the AR sessions. Most students reported moderate levels of mental demand but lower frustration and higher performance scores, indicating a positive balance between challenge and learning effectiveness.

In addition, time-on-task analysis revealed a significant difference in engagement between the learning modalities. Students voluntarily spent more time interacting with the immersive AR tools, averaging 43 minutes per session, compared to just 21 minutes when using traditional software tutorials.

This increased time-on-task not only reflects higher intrinsic motivation and user engagement but also correlates with improved learning outcomes observed in subsequent assessments.

Qualitative Findings**Student Focus Groups**

Three focus groups (8 students each) were conducted at the end of the semester. Thematic analysis of transcripts yielded several key insights:

Visualization and Comprehension: Students consistently reported that “seeing” the mechanism in 3D made it easier to understand how parts interact, particularly for gear trains and crank-slider systems Figure 12.

Engagement: Students expressed that learning felt more like “exploring” than studying, which increased motivation.

Confidence Building: Several students indicated that immersive learning reduced anxiety in labs because they had already practiced virtually.

Box 15**Figure 12**

Student explaining how easy is to interpret assemblies using AR-Apps

Sample comment:

“Before, I was just guessing what would happen when parts moved. In AR-Apps, I can see the motion of components right away. It’s like having x-ray vision.”

Instructor Feedback

Instructors noted improvements in classroom dynamics and learning depth:

Conceptual Discussions: Students asked more precise, technically informed questions after AR sessions.

Independent Learning: Students were more inclined to experiment independently using the provided applications.

Assessment Quality: The quality of student projects and design reports improved noticeably, with better articulation of spatial and functional reasoning.

One faculty member remarked:

“This is the first time I’ve seen students actually excited about understanding mechanism constraints—they weren’t just completing assignments; they were exploring design ideas.”

Observational and Interaction Data

Interaction logs from the AR-Apps applications revealed distinct usage patterns:

- Average number of model manipulations per session: 96
- Average time spent in virtual assembly task: 22 minutes
- Most common actions: zoom, rotate, isolate component, view section cuts

These metrics suggest high levels of interactivity, aligning with engagement survey data. No technical issues were reported during classroom deployment, aside from brief headset calibration times, which were resolved through orientation protocols.

Discussion

The data suggest that integrating AR-Apps into the CAD and mechanisms curriculum yields substantial benefits in both cognitive and affective learning domains. Gains in test performance, spatial reasoning, and student confidence demonstrate that immersive technologies are not just motivational tools but effective pedagogical instruments when properly aligned with learning goals. The improvements in spatial understanding and component interaction are particularly significant for engineering education, where 3D thinking is critical for success in design, simulation, and problem-solving.

Furthermore, the interactive and exploratory nature of the tools contributed to more active learning behaviors, a core principle in modern engineering pedagogy.

Conclusions

The study demonstrates that the strategic development and integration of AR-Apps applications into STEM education significantly enhance student learning in CAD and mechanism courses. By aligning immersive tools with curricular objectives, and by designing interactive, pedagogically grounded learning scenarios, the project achieved measurable improvements in student performance, engagement, and spatial reasoning ability.

Quantitative results showed statistically significant gains in conceptual understanding and spatial cognition, particularly in areas traditionally considered difficult, such as 3D visualization and mechanical motion prediction. Students not only performed better on assessments but also reported higher levels of engagement, confidence, and motivation. Qualitative feedback further confirmed that AR-Apps supported deeper learning and enabled students to bridge the gap between abstract concepts and physical intuition.

From an instructional perspective, faculty observed enhanced classroom dynamics, more meaningful student questions, and higher-quality project submissions. The immersive tools promoted active, exploratory learning and supported a learner-centered pedagogy aligned with the demands of modern engineering practice.

The success of this implementation highlights the potential of immersive technologies to transform the way engineering concepts are taught and understood, particularly in disciplines where spatial awareness and system-level reasoning are critical. These tools also open new possibilities for blended and remote learning, offering rich, interactive environments beyond the limitations of physical labs.

Future work will focus on expanding the scope of the applications to include dynamic system analysis, control simulation, and integration with digital twins for predictive maintenance training.

Additional studies are also planned to explore long-term learning retention, scalability across different institutions, and accessibility for diverse learner populations.

Conflict of interest

The authors declare no conflicts of interest.

Author's contribution

Manuel Meraz Méndez: Contributed to the project idea, research method, algorithms design, virtual reality design apps, augmented reality design apps and technique.

Guadalupe Corral Ramirez: Contributed to the research method and article writing.
Professor-

Luis Enrique Muñoz López: Contributed to the research method, data analysis, and results

Jorge Duarte Loera: Contributed to the blue print drawings and 3D modeling design

Octavio Chimal Corrales: Contributed to the AR MetaQuest design applications

Humberto Alejandro Arrollo Salado: Contributed to the AR Android design applications

Francisco Iván Gallegos Gonzalez: Contributed to modeling 3D and Blue prints design

Availability of materials and data

MetaQuest Headset (2), Android tablet (3), Unity software, Solidworks software

Founding

The authors acknowledge the support received from various areas at the Technological University of Chihuahua and the PRODEP program.

Acknowledgments

The authors express their gratitude for the support received in various areas to the Technological University of Chihuahua (Department of Industrial Maintenance Engineering) and the Technological Institute of Chihuahua-TecNM (Department of Basic Sciences).

ISSN: 2523-0344

RENIECYT-SECIHTI: 1702902

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