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Utilizing Augmented Reality and 3D Models to Enhance Conceptual Knowledge and Visualization of 3D Problems in Engineering Mechanics Courses: Case Study of Statics

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Utilizing Augmented Reality and 3D Models to Enhance Conceptual Knowledge and Visualization of 3D Problems in Engineering Mechanics Courses: Case study of Statics

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Abstract

Engineering Mechanics courses present unique challenges for engineering students, particularly when dealing with three-dimensional (3D) problems. The ability to visualize where forces act and their directions is fundamental, yet many students struggle with this aspect. Insufficient visualization skills can impede the learning process, making it difficult to grasp additional complex steps in solving 3D problems. This study explores the rationale and implementation of augmented reality and digital 3D models to assist students in overcoming these challenges.

To address these issues, a mobile phone application was developed, incorporating AR technology to enhance students' understanding of 3D Statics problems. Additionally, students were exposed to digital 3D models during lectures focused on 3D problems. The aim is to provide students with more frequent exposure to 3D concepts and to introduce alternative ways of visualizing problems beyond the confines of traditional two-dimensional textbooks. The working hypothesis is that immersing students in 3D scenarios through AR and providing them with interactive 3D models will help them in gaining a more profound understanding of course concepts, particularly those related to 3D problems. Findings and insights from this study contribute to the ongoing efforts in engineering education innovation and provide students with the tools they need to excel in complex 3D problem-solving scenarios.

Background

Courses in engineering mechanics, such as Statics, Mechanics of Materials, and Dynamics, typically form a fundamental component of engineering education. They lay the groundwork for various subsequent courses across diverse engineering disciplines, including aerospace, civil, construction, and mechanical engineering. A solid grasp of engineering mechanics is essential for students, as it facilitates their understanding of later courses, such as Structural Analysis, Machine Design, and other specific courses in each field of engineering. Statics, in particular, can be considered the most crucial, serving as a prerequisite for all other engineering mechanics courses and, consequently, most downstream courses within engineering programs.

Even though Statics is recognized as a critical course, student performance is typically regarded as poor [1]. In particular, basic learning objectives such as proficiency in drawing accurate free body diagrams or accurately solving equations of equilibrium remain unfulfilled. Some of these issues are recognized to originate from lack of geometry, trigonometry, and algebra skills, however, many are unique to the subject of Statics and due to conceptual misunderstandings. Additionally, a poor performance in Statics is shown to be directly correlated to student's final cumulative GPA and their retention in engineering [2].

Many educators have explored strategies to enhance students' conceptual understanding of Statics, aiming to improve their overall performance in the course. One method for reinventing the way Statics is taught was proposed by introducing a more hands-on and physical approach to learning the concepts [3]. With this, several demonstrations are proposed with props used for students to see and feel interactions involving forces. Other research using physical models has been used for the conceptual understanding of specific topics in Statics such as trusses [4, 5].

Among the different topics, the lack of conceptual understanding among students is particularly pronounced when dealing with three-dimensional problem. The authors have observed that students often struggle to identify which components of forces are to be included in each equilibrium equation and struggle to draw reaction forces correctly or overlook them entirely in their free-body diagram (FBD). There has been much work related to FBDs in literature over the years [6, 7, 8], however, the research on visualizing 3D FBDs has been limited. Other issues show an inability to decipher the direction of moments in 3D or comprehend the conceptual meaning behind the computational results. In response to these issues, the authors aim to not only build upon prior research to address these issues in Statics, but also use new and advancing technologies, such as augmented reality (AR) and 3D computer-aided modeling, that may be beneficial to students' learning.

In a recent systematic review of AR in engineering education, the predominant focus of AR studies in engineering involved technical drawings and visualization, particularly in the realms of electrical and construction engineering. The majority of the evaluated studies reported an improvement in students' academic performance, coupled with positive perceptions from students regarding the use of AR. The review highlighted that existing engineering AR applications generally lack high levels of user interactivity and functional characteristics, indicating significant potential for future developments in AR within engineering education [9].

A common application of AR in engineering education revolves around 3D visualization and spatial skills enhancement [10, 11, 12, 13, 14]. Research in this field focused on creating AR tools that enables users to augment 3D models, fostering spatial awareness in relation to 2D technical engineering drawings. Findings indicated that participants who underwent AR training demonstrated more substantial improvements in spatial ability compared to those without AR training [11, 13]. A similar study was conducted incorporating tangible physical models along with AR to enhance spatial skills [14]. While the study revealed that AR alone did not significantly impact the transformation of 2D technical drawings to 3D objects, tangible models did contribute positively to students' ability to map 3D objects to 2D technical drawings.

While previous studies using augmented reality (AR) to enhance spatial awareness and visualization in engineering education have yielded mixed results, there are numerous advantages that encourage further investigation. Some advantages of using AR and digital models include the ease of making changes, not succumbing to the possibility of physical damage, cost-effectiveness compared to physical materials, and the capability to showcase large-scale objects that would otherwise be impractical to bring into the classroom. The drawback, however, to AR and digital models lies in the labor costs associated with Computer-Aided Design (CAD) work and the time required to master the relevant software.

In the following sections, the need and justification for 3D visualization tools related to many topics in engineering Statics is discussed along with the results of an entry-level survey of the students in Static courses are presented. Then the process for constructing these tools and the procedure to implement them into the classroom is discussed. Lastly, the results of using an experimental and control group to test their effectiveness is summarized and discussed.

Introduction to Student Challenges

To gain a better insight into students' perceived challenges with 3D problems, a brief survey was conducted in Fall of 2022 following the completion of all 3D topics and subsequent testing on those topics. The questions and corresponding results are outlined in Figure 1. The findings indicate that, on average, many students lack confidence in their understanding of material related to 3D problems and their ability to visualize them. This sentiment is reinforced by exam scores taken in the same semester, with problems involving 3D vector addition, 3D particle equilibrium, and 3D moment of a couple all averaging below 75%. Additionally, problems related to 3D moment of a force about an axis and 3D simplification averaged below 60%.

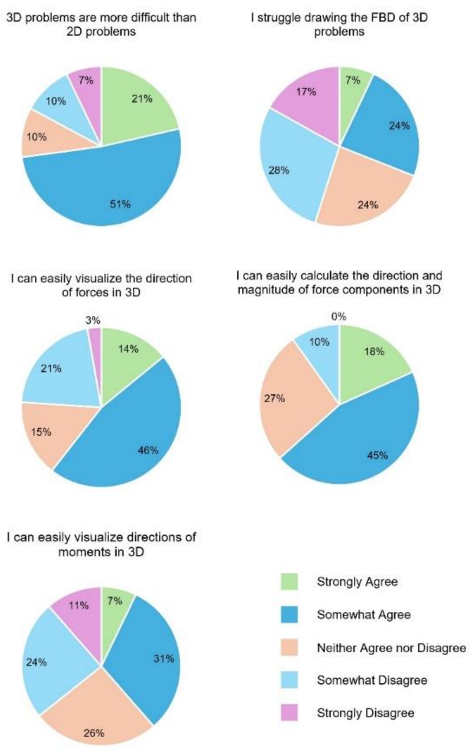

Figure 1. Results of students' self-assessment of the 3D visualization problems.

Upon reviewing survey results and considering additional feedback from students, it was identified that many students require more effective approaches to visualize 3D problems effectively. The specific topics covered in 3D or with a significant emphasis on 3D are outlined in Table 1. While not all institutions prioritize every one of these topics or content areas in their Statics course, the authors posit that this material aids in cultivating crucial skills essential for future courses and successful engineering careers. Each topic's specific content corresponds to a single class period, constituting 10 days, or approximately 27% of the course duration in a traditional 16-week semester that is dedicated to teaching of 3D content.

Table 1. 3D Topics taught in statics.

Topic	**Specific Content by Day**
Vector Resultants	Coordinate Direction Angles In-Plane and Out-of-Plane Angles (Transverse and Azimuth Angles)
	Position Vectors Unit Vectors
Dot Product	Angle between vectors Projection onto a line
Particle Equilibrium	3D Particle Equilibrium
Moments	Scalar Analysis using the Right Hand Rule Vector Analysis using Cross Product
	Moment about a line or axis
	Moment due to a Couple
System Simplification	A resultant force and couple-moment
	A resultant force at specified coordinates in a parallel force system Reduction to a Wrench
Rigid Body Equilibrium	3D Rigid Body Equilibrium

Methodology

In both the control and experimental class, each of the topics from Table 1 was taught in a conventional face-to-face classroom setting. Initially, the topic and potential underlying theories were introduced. Once the necessary information was presented, in the experimental group a 3D model illustrating the problem-solving process was displayed. However, these models were not merely designed for rotation or panning to showcase to students. Instead, vectors, angles, axes, and other components were strategically grouped to enable them to be selectively hidden or revealed in a logical sequence, enhancing the coherence of the topic's procedural explanation. An illustration depicting certain steps in elucidating a resultant force in a parallel force system is presented in Figure 2. Numerous other instances of these models are featured in Figure 3, each potentially containing additional vectors, components, or steps that are selectively concealed or revealed to align with the teaching sequence.

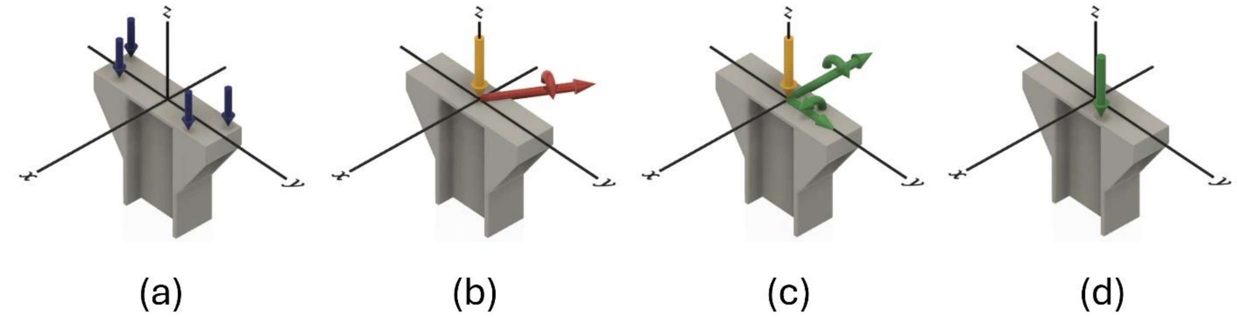

Figure 2. Equivalent system process shown through 3D models a) original loading, b) reduction to resultant force and couple-moment, c) resolving resultant couple-moment into components, d) single resultant force at specific coordinates.

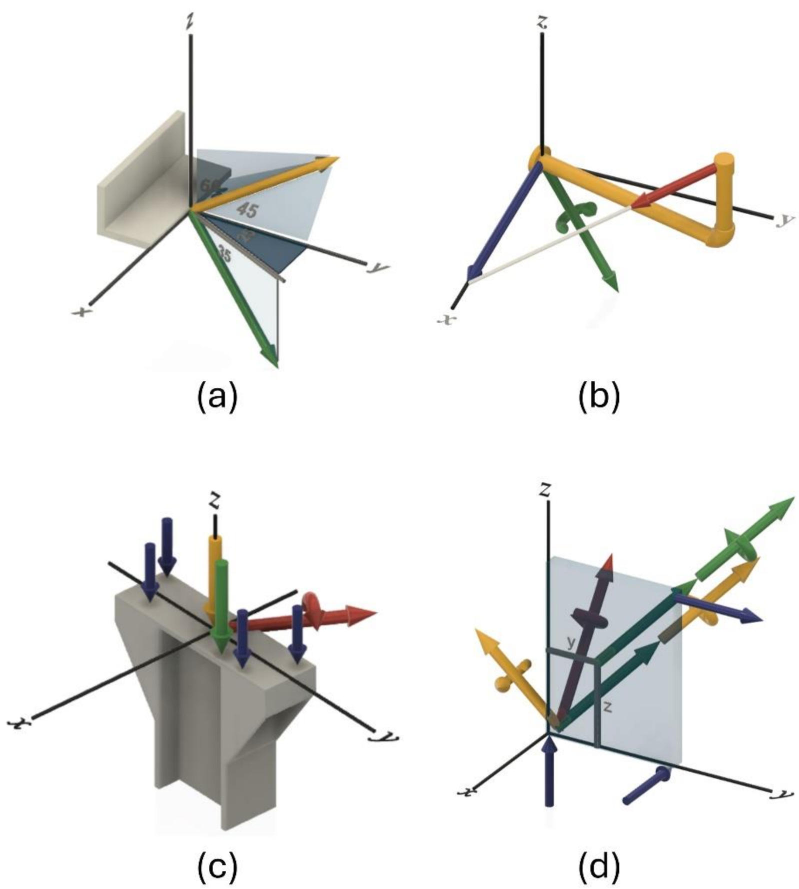

Figure 3. Examples of 3D CAD models used to introduce and explain various topics: a) coordinate direction angles and in-plane and out-of-plane angles, b) moment about a point using the cross product, c) reducing a parallel force system to a single resultant force, d) reducing a system to a wrench.

StaticView creation

The subsequent phase of this research involved placing the control of 3D models into the hands of students. While passive viewing of models may be considered more advantageous than encountering a representation of a 3D problem on a 2D textbook page, the introduction of user interactivity has the potential to significantly enhance these benefits [9]. This is why an augmented reality application, called StaticView, was built. StaticView recognizes a variety of 3D particle equilibrium problems as target images and then augments both a realistic 3D model and an FBD that the user can view and interact with in a way that could not be done through conventional textbooks as shown in Figure 4. This section describes the process taken for creating StaticView as well as its use in the classroom.

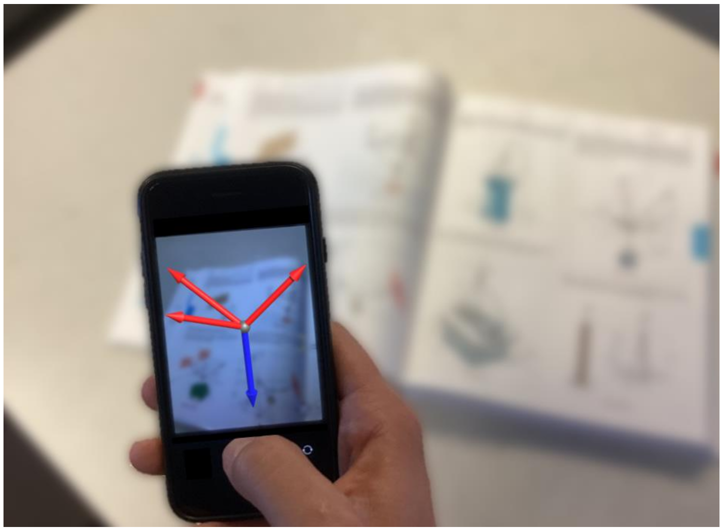

Figure 4. StaticView used to interact with statics problems from the textbook.

The initial phase in developing StaticView involved choosing problems that align with the project's objectives. Given that StaticView aims to aid in visualizing 3D forces and their directional references, 3D particle equilibrium problems were the chosen focus. A variety of problems using coordinate direction angles, in-plane and out-of-plane angles, position vectors, and a combination of these were used in the app development. Digital copies of these problems were uploaded to Vuforia which automatically selects target points on the unique image that the AR camera will be able to detect and identify. These problems are able to be detected through printed out problems, either in a glossy textbook or otherwise printed, and can be detected through LED or LCD screens from problems in ebooks.

CAD was employed to craft three-dimensional models for each of the chosen problems. The objective was to closely replicate each problem while ensuring the models were as realistic as possible. This involved maintaining identical proportions and angles as the original problems, as well as incorporating realistic objects, textures, and colors. Examples of these models are depicted in Figure 5. The aim for users of StaticView is to experience a sense that the augmented model is emerging convincingly from the page.

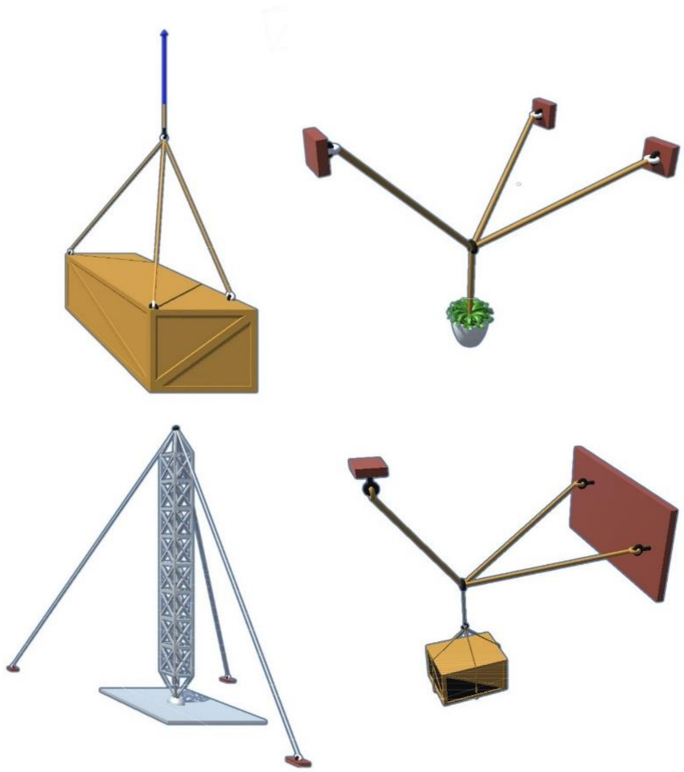

Figure 5. Realistic CAD models used in StaticView.

Unity was selected as the platform for building this app. The target images were uploaded, and the 3D CAD models were attached to these such that when the AR camara detects a target image, the corresponding model will appear. In addition to the realistic CAD models, FBDs were created inside of Unity and attached to each respective target image. Building these FBDs inside of Unity itself rather than a program designed specifically for CAD was chosen to assign functions more easily to individual force vectors, labels, or angles such as making them appear or rotate as needed.

The user interface of StaticView was built as simple as possible. When loading the app, the user is immediately presented with a camera view so that specific problems can be detected as target images when they come into focus shown in Figure 6. Once a target image is detected, the 3D model appears on screen which gives the user multiple options for exploration. One option is to zoom into the model using the “zoom” slider bar which allows the user to enlarge the model to see details more clearly. Another option is to rotate the model using the “rotate” slider bar which will rotate the model about the vertical z-axis so users can view the model from all sides while still maintaining a sense of direction. The logic for these slider bars was written as a simple C# script within Unity. The third option is for the user to move their device around as if the 3D model was physically present. This is a built-in feature of the AR camera in Unity. A combination of these three exploration options allows the user to have precise viewing angles of the model based on what is desired.

In addition to the 3D model that appears, the user has an option to toggle to a FBD view. This view shows all forces with appropriate variable names, directions, and references. It could be argued that having this FBD presented to the user could hinder the learning process since a critical part of Statics is the ability to draw a FBD correctly, however, because these are particle equilibrium problems, the FBD is very simply conceived. Additionally, users would still need to draw and label their own 3D particle equilibrium FBD which still requires spatial awareness and knowledge of appropriate labels even if they are viewing a model of the FBD on their device.

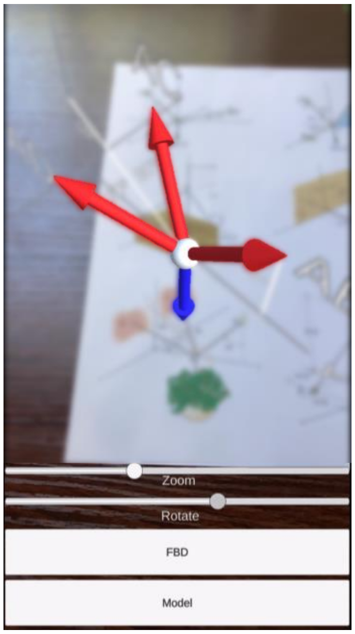

Figure 6. User interface of StaticView.

StaticView implementation

StaticView was launched as an iOS application via TestFlight. A license is required to distribute apps in TestFlight, but it was an opportunity to release to a specified distribution list without launching publicly on an app store. Because some students did not have devices that were compatible with the application, an opportunity was given for students to checkout devices from the department that would allow them to use StaticView. It was expected that most students would still not participate in downloading or using StaticView on their own, so additional exposure was also implemented.

Similar to using the 3D models in class, StaticView was also shown to students in the experimental section through example problems related to 3D particle equilibrium. The instructor's phone screen was mirrored to the classroom screens showing how the application recognizes the target image and augments the 3D model. The model and FBD were scaled, rotated, and the view angle was changed so students could conceptualize the problem and see the direction of the forces more clearly. A hand-written solution to the problem was completed after students viewed these augmented models which were used as talking points when calculating components of forces in the problem.

Results and Discussions

To determine the effectiveness of StaticView and the use of 3D CAD models in the classroom, a study was conducted in the Spring of 2023 where two sections of Statics were taught sequentially in the same room by the same instructor. Enrollment in the Spring semester is usually lower in comparison to the Fall semester, primarily because most engineering departments at the university schedule students to take Statics in the Fall semester. Because of this, the Spring semester sections are largely comprised of students who did not successfully complete the course the prior semester or students who have met the prerequisites and are taking the course a semester early. More than 40% of students in this study had previously been enrolled in Statics in at least one prior semester.

In accordance with the Institutional Review Board (IRB) regarding human subjects, students always had the option to hold their data from being used in this study. This initially resulted in 102 total students, however, this number decreases throughout the study due to student drops and other factors that lead to lack of participation in various activities, quizzes, or exams where data was collected. Students dropping the course caused data sizes to decrease throughout the semester, however, data was always analyzed with as many students as possible for each data point. Data collected from students is summarized in Table 2 with both demographic data as well as prior history with Statics and courses that involve 3D problems.

Table 2. Student history data.

	Control Section	**Experimental Section**
Enrollment	55	55
Allowing Data Collection	50	52
Gender		
Male	43 (86%)	48 (92%)
Female	7 (14%)	4 (8%)
Prior Enrollment in Statics		
Yes	22 (44%)	20 (38%)
No	28 (56%)	32 (62%)
Prior Engineering Graphics Course		
Yes	30 (60%)	32 (62%)
No	20 (40%)	20 (38%)
Enrollment in Calculus III		
Completed	33 (66%)	26 (50%)
Currently Enrolled	9 (18%)	19 (37%)
Neither completed nor enrolled	8 (16%)	7 (13%)

Several data points were collected throughout the semester including a pre-semester baseline quiz, four quizzes along the semester, three partial exam scores, and a post-semester quiz. The pre-semester baseline quiz was a six-question quiz with 3D figures to gauge student's ability to visualize and work with 3D problems. Only prerequisite material was needed to solve problems with no Statics being involved. The primary purpose of this quiz was to provide a baseline of students' 3D visualization and to compare any differences between the experimental and control sections. The same six-question quiz was then given on the last day of the semester so that a paired test could be performed to measure differences. Extra credit was offered for both pre- and post-semester quizzes as an incentive for correct answers to ensure that students performed to the best of their ability.

Conceptual quizzes were administered during the subsequent class period when the new material was introduced. These consisted of one or two questions that required students to interpret, visualize, or calculate from a 3D figure. For each exam where a 3D problem was presented, the percentage that students scored on that particular problem was also used as a data point. The quiz and exam scores were then used to compare the groups using a Wilcoxon test.

Both the pre-semester baseline quiz and the post semester quiz showed no significant differences in results between the experimental and control groups. Additionally, there were no significant differences in any of the exam scores related to the 3D problems.

There were only two conceptual quizzes that were given throughout the semester that did have significant results. A quiz on the dot product and parallel/perpendicular components of a vector along a line showed that the control section actually scored significantly higher than the experimental section ($p = 0.035$). The other quiz that showed a significant difference was on breaking up a force into x, y, and z components that had difficult geometry. The results showed that the experimental section scored significantly higher than the control section ($p = 0.01$).

While no statistically significant evidence was found that the overall effectiveness of StaticView or 3D CAD models was either positive or negative, there were several qualitative results that were promising. In a survey given after all 3D modules were concluded, several students shared comments that mentioned either StaticView or the 3D CAD models shown in class helped them grasp the material or helped them think about it differently. Some of these direct quotes from students are shown below:

> *They help to actually visualize what the problem is doing.*
>
> *They helped create a better method of visualization in my head when working on homework problems*
>
> *Nice to have, helped with my understanding of moments*
>
> *I do think they were beneficial, they didn't take up too much time but helped get an "off paper" idea of what was happening and really helps you see the angles and grasp them*
>
> *The 3D models were very useful when first discussing a new concept because the model helped in showing the direction.*

It was refreshing to see a nice interactive visual alongside the usual problems we had in class. Also helps to break up the monotony of working on problems on a worksheet and have something to help visualize the problem at the same time.

Conclusions

Statics is a very critical course in most engineering disciplines due to many downstream courses building on the fundamentals of Statics. Even with the importance of this class, it is seen by the authors and other published literature that student performance in Statics is not satisfactory. Students have acknowledged some of their shortfalls in Statics through the survey presented in this paper, specifically as they relate to their ability to visualize and work on problems in three-dimensions. It is therefore important to address these shortfalls to ensure that students complete Statics with the necessary conceptual knowledge and visualization skills needed to work with 3D problems in their upper-level courses and future career as engineers.

This paper aims to provide insights into the implementation of 3D visualization in engineering courses, with a specific focus on engineering Statics. The objective is to enhance students' conceptual understanding of diverse topics and facilitate the visualization of 3D problems. To achieve this goal, computer-aided design models and an augmented reality mobile-phone application were developed. While the results may indicate that the overall impact of employing StaticView and 3D CAD models did not demonstrate a statistically significant difference in performance outcomes, individual feedback highlighted a positive influence on certain students. Moreover, the findings suggest that incorporating AR and CAD models in this manner did not impede students' learning outcomes. Consequently, it is concluded that the utilization of these teaching methods can serve as a valuable resource for students. The encouragement of further exploration into 3D visualization methods and examples is advocated, particularly within the realm of engineering, specifically in Statics.

Further exploration in assisting students with 3D visualization in Statics is being investigated with both improvements to CAD models, additional features using AR, and other methods. Specifically, the adoption of using these 3D visualization techniques early in the class may be one way to improve results. StaticView was used as a tool primarily for 3D particle equilibrium problems, however, students are exposed to 3D force resultants prior to this topic. CAD models were shown in class during 3D force resultants, but the AR application StaticView was not made available for these types of problems. Future work will be completed more variety of StaticView problems, more specific CAD models used as well as the timing on when they are introduced to yield more meaningful results.

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