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Developing Augmented Reality Applications to Help Engineering Students Learn Spatial Structural Engineering Concepts

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Development of Augmented Reality Application to Aid Engineering Students in Learning of Spatial Structural Engineering Concepts

Abstract

In traditional mechanics-oriented classes, experience and the literature have shown that students are often challenged with conceptualizing complex three-dimensional behavior. Within the context of structural engineering and mechanics, the challenges manifest in scenarios related to linking this three-dimensional behavior with member response such as elastic buckling of columns and critical locations for shear and moment. While solutions such as props and videos have been used as examples in the past with some success, these tools do not spatially represent complex structural behaviors and are also limited to one-way interaction where the learner receives the information but cannot interact with the tools.

This project leverages mobile augmented reality (AR) designed to help students visualize complex behaviors (deformation, strain, and stress) structural components with various loading and boundary conditions. The tool, STRUCT-AR utilizes finite element models pre-loaded into a mobile AR application that allows users to interact and engage with the models on their mobile device or tablet. Our vision of this technology is to provide a complementary teaching tool for enhancing personalized learning wherein students can leverage the technology as a learning companion both within the classroom and outside to better understand structural behaviors and mechanisms that are challenging to convey in a traditional 2D learning environment. This study uses a pilot study to evaluate how undergraduate and graduate students who have previously taken an introductory course on structural system design perceived the app. The purpose of this pilot study is to evaluate the usability of the app, its ability to improve spatial visualization ability, and to collect feedback on the app functionality. Study participants were asked to complete a pre and post-survey and the IBM Post-Study System Usability Questionnaire after engaging with the AR app on an iOS tablet. Results discuss how participants viewed the app in terms of its usability and usefulness and recommendations for tool refinement. Future work will be focused on conducting another pilot study after tool refinement before app deployment in a classroom setting.

Keywords: augmented reality, mixed reality, mobile augmented reality, structural design, structural mechanics, finite element method, visualization, personalized learning, engineering education

Introduction

Mechanics serves as the foundation for undergraduate students specializing in mechanical or structural engineering, with concepts such as displacements, torsion, and buckling revisited in more advanced courses. However, students often struggle visualizing how these concepts present themselves in a three-dimensional environment and how cross sections and materials play a role in these concepts [1]. Tools such as simulation software, videos, and props have been previously used by instructors to replicate these complex behaviors of structures; however, these tools do not spatially represent this behavior [2–4]. Videos and simulation software are also limited to one-way interaction, where students cannot interact with the structures being modeled.

Research has shown that interactive simulations improve cognitive gain outcomes, as well as increased interactions among students [5, 6]. Integrating these simulations can be done in four virtual-real environments: 1) virtual reality (VR), where the entire environment is virtual; 2) augmented virtuality, a subbranch of mixed reality (MR), where real objects are integrated in the virtual environment; 3) augmented reality (AR), where 3D objects are overlaid in the real environment and 4) reality. AR has been utilized in industrial processes training, tourism and heritage reconstruction and, in gaming [5]. In higher education courses, AR has been used to teach human anatomy, mechanical parts and, linguistics [7]. In engineering education, AR has been shown to improve spatial abilities [5]. As an engineering-context example comparable to our study, Alvarez Marin et al. [8] deployed an AR app to third and fourth-year engineering students that simulated series and parallel circuits. The app required users to scan QR codes representing different components of the circuit such as resistors, light bulbs and, batteries. In another study by Nadeem et al. [9], an Android marker-less AR app to teach electrical engineering undergraduate students about finite-state machine concepts. Users had tasks to complete to evaluate the app's performance and interacted with the app with a finite-state machine handout.

In the context of AR and MR in construction and structural engineering education, there have been several published applications. Shirazi and Behzadan [5] implemented an AR app, CAM-ART, that utilized a QR code to enhance textbook images with sounds, videos and 3D models. Students that used CAM-ART reported that they were more motivated and interested in the subject. However, students also reported that they were unable to interact with the app and concentrate on the lecture simultaneously. Olbina and Glick [10] deployed mixed reality apps to view and build a frame from wood, where undergraduate students were asked pretest and post-test questions after using the apps. Students that used AR and VR had some improved knowledge, improved communication skills and improved visualization. Hu et al. [11] used AR in a Project and Facilities Management undergraduate course to present simple theories in structural engineering. Students that used the app stated that it improved their understanding of learning outcomes and students achieved higher quiz scores. Kraus et al. [12] developed a mixed reality tool to design reinforced concrete corbel and a steel frame. Students who participated in the pilot study collaborated more with other students and were also motivated to study the subject. Turkan et al. [3] launched an iOS marker-based app for third year undergraduates that recognized textbook and assignment examples and displayed pre-calculated deflections and loads. While students reported an improved learning experience, students were also overwhelmed and found the app difficult to use.

Given the limited integration of AR in structural engineering courses and its potential benefit to students who struggle with visualizing complex structural phenomena, this study presents STRUCT-AR, as a continuation of previous work by the authors [13, 14] as part of an ongoing study on the formation of engineering intuition in structural engineering. STRUCT-AR is a marker-less AR application designed to address the limitations in previous AR studies and visualize interactions of components in large-scale infrastructure systems. By being marker-less, the app can be used by students at any time without the use of a textbook or handouts. To test students' perception of STRUCT-AR, a pilot study targeted at undergraduate and graduate students who had previously taken an introductory structural design course, was launched. Identical beams with varied load distributions were presented to participants to understand if these models aided their theoretical understanding of stress and strain states, while also understanding if STRUCT-AR was usable through a usability questionnaire. This preliminary study serves as the initial phase in improving the app before it is used in the classroom.

Methods

Augmented Reality App

This paper builds on the work presented in [13, 14] which introduced an augmented reality app with three-dimensional, interactive structural models in order to address the need for this by students and educators. The current project focuses on evaluating the app with new models aimed at understanding how stress states and strain states change with different loading conditions, conducting interviews and asking participants to take a usability study.

Figure 1 illustrates the app's current workflow, previously mentioned in [14]. A finite element analysis (FEA) software is initially used to create the models that will be displayed in the app. Upon running a successful simulation, the element and node connectives, the location of nodes in the global coordinate system, the stress, strain and displacement information are saved and imported into the app in the form of CSV files.

Once the user selects a model, as shown in Figure 2, the program loads the undeformed structural model data from the applicable CSV file. Upon inputting the magnitude of the load (the default option being 1 kip) (Figure 3), the user then identifies the ground plane, as shown in Figure 4. Figure 5 displays how the selected undeformed uniform loaded beam appears in the user's environment. Once the user presses the 'Play' icon, the app displays a dynamic visualization of the deformation scaled by the user-defined load magnitude until the final deformation state is reached. Users can the examine and interact with the model results by viewing the results as contours throughout the member geometry, rotating the model or moving their device around the model to view it at various perspectives. An example of this is shown in Figure 6. Users can also select the drop-down menu on the screen to view other response variables and their corresponding results, such as strains and stresses. Individual node results can also be viewed by pressing on the model mesh. Future work of the app includes user-defined models and the ability to change the material properties and loading conditions of existing models.

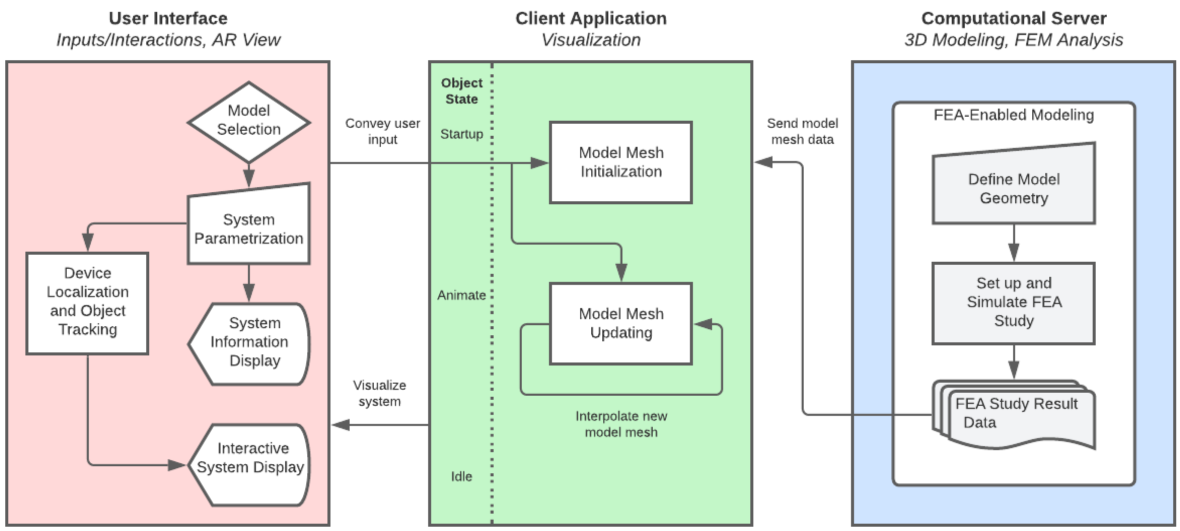

Figure 1: Workflow of current version of app [14]

Figure 2: Opening screen of app with models focused on in this study

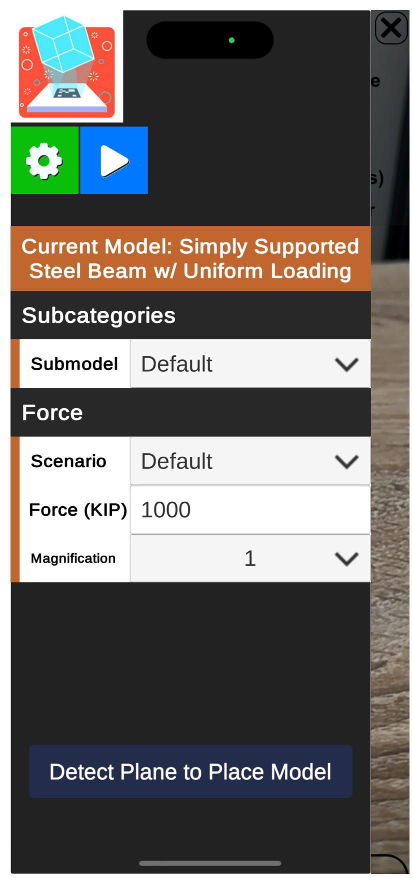

Figure 3: Menu to change magnitude of loads

Figure 4: Identifying the ground plane

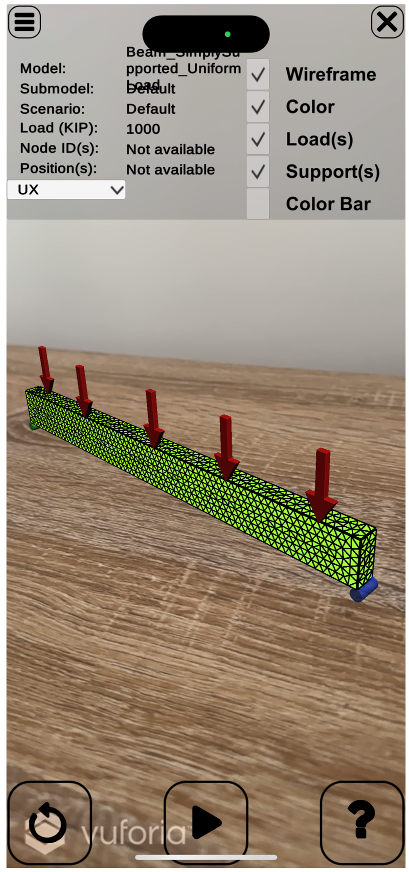

Figure 5: Uniformly loaded beam before deformation

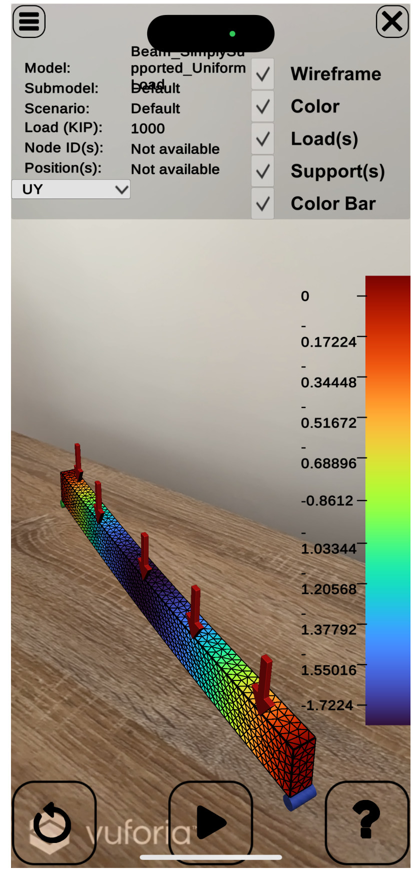

Figure 6: Uniformly loaded beam after deformation

Pilot Study

Undergraduate and graduate civil engineering students from the University of Virginia were recruited for the study. To be eligible, students had to be 18 years old or over and have taken Introduction to Design of Structural Systems at the University of Virginia or another comparable structural design course at another institute. A total of 5 students participated in the pilot study, two graduate students and three undergraduate students. The limited participants' pool is attributed to both the University of Virginia's small civil engineering program and the restricted current deployment structure.

Participants completed the following procedure, which took approximately 90 minutes:

1. Fill out a demographic form listing their gender, year level (undergraduate or graduate) and their experience with augmented reality.
2. Spend 5 minutes of unguided exploration time using the app on an iPad in which they could ask questions on how to use the app if necessary. After the 5 minutes, the goal of the app as well as how to use it, was explained to participants.
3. Spend 10 minutes to explore the three models shown in Figures 7, 8, 9; a simply supported

steel beam with uniform loading, a simply supported steel beam with midpoint loading and a simply supported steel beam with two point loads 1/3 from the supports. The beams had the same material properties, length and cross sections. Participants were asked to observe how the stress state and strain state changed for each condition and if this aligned with their conceptual understanding.

4. Once exploring the app was completed, the IBM Post-Study System Usability Questionnaire (PSSUQ) [15] was immediately taken. The PSSUQ is a 19 question survey assessing the satisfaction of users interacting with a system.

5. Interview with the researcher about their experience with their app and if they would add any features to the app to aid in their use

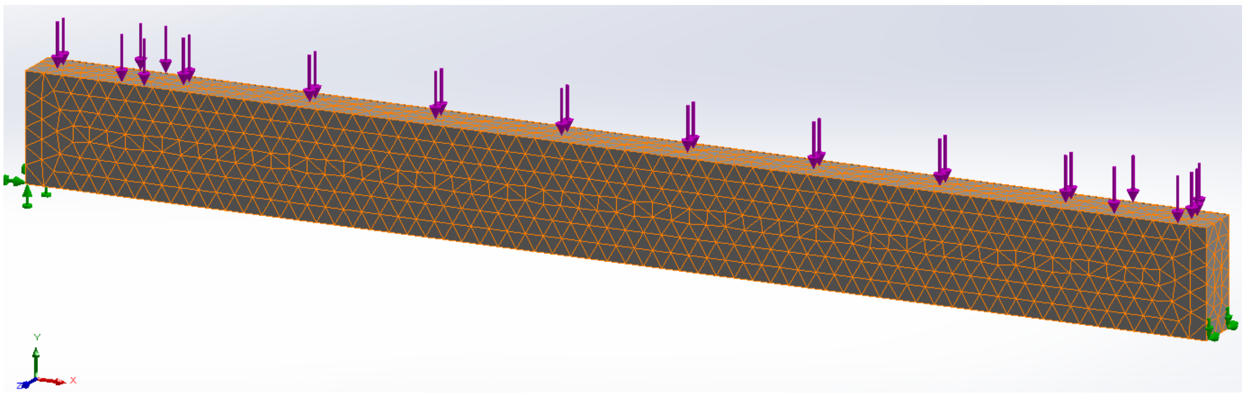

Figure 7: Simply Supported Steel Beam with Uniform Loading

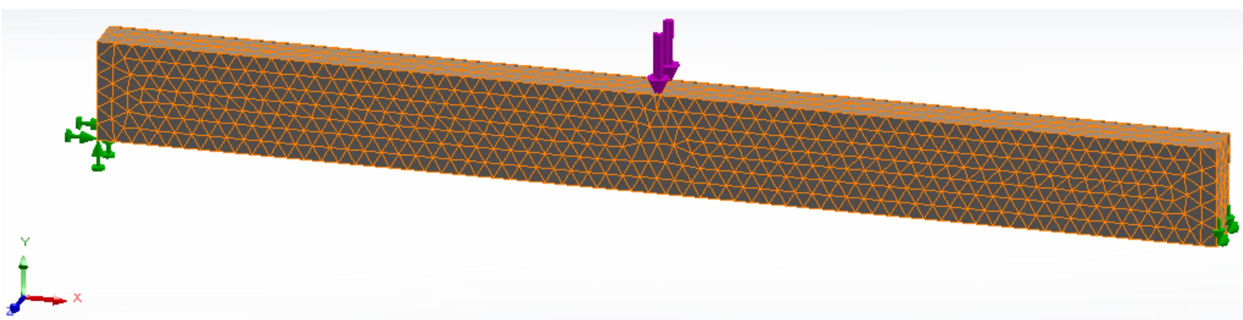

Figure 8: Simply Supported Steel Beam with Midpoint Loading

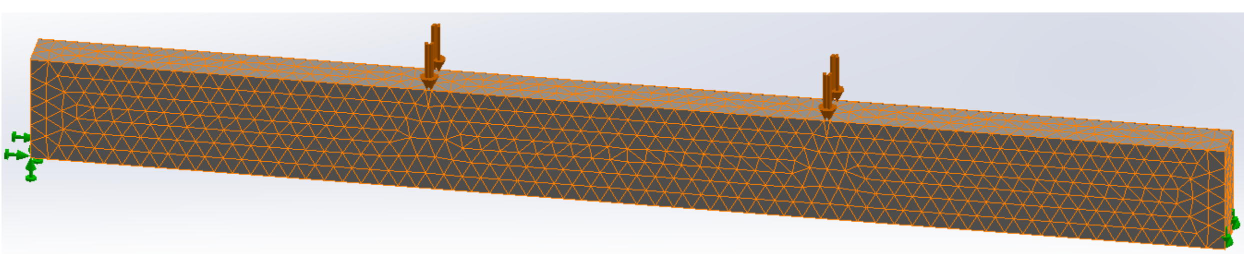

Figure 9: Simply Supported Steel Beam with Two Point Loading

Results

Table 1 lists the statistics of the PSSUQ responses, with responses given on a 7-point Likert scale where scores range from a 1 (strongly disagree) to a 7 (strongly agree). System usefulness (SYUSE) is measured by statements 1-8; information quality (INFOQUAL) is assessed by statements 9-15; interface quality (INTERQUAL) is measured by statements 16-18 and overall satisfaction (OVERALL) measured by all 19 statements [16]. As shown in the table, INFOQUAL and OVERALL contained the lowest minimum at ”strongly disagree”, which was associated with the statement ”The system gave error messages that clearly told me how to fix problems.” This was also mentioned by participants in the long-form questions. SYSUSE had the highest mean, with the most highly rated statement being ”I believe I could become productive quickly using this system”. Participants also agreed with the statements ”The information was effective in helping me complete the tasks and scenarios” ”The information provided for the system was easy to understand” and ”Whenever I made a mistake using the system, I could recover easily and quickly”.

Table 1: Participant’s PSSUQ Responses (N=5)

	Mean	Std. Dev.	Min	Max
OVERALL	4.766	1.510	1	7
SYSUSE	4.897	1.418	2	7
INFOQAUL	4.677	1.576	1	7
INTERQUAL	4.553	1.628	2	7

All participants, specifically those that identified as visual learners, had positive comments on the app’s potential to aid students taking structural design classes, specifically its engaging aspect. This observation added value to the app, despite it not being specifically designed to aid visual learners. Participants mentioned that the app gave them the ability to observe models at different angles and engage with them more than other 2D simulation or design software. Participants also praised the interface of the app, stating that it was aesthetically pleasing.

All participants initially struggled with using the app and required guidance on how to use it. Many of the participants stated in their intake form that they had no prior knowledge of AR technology, which may have contributed to their initial confusion. The application also includes a restricted assistance menu and lacks an initial tutorial, which could have enhanced the participants’ initial understanding of the application. Two participants experienced a glitch or crash when using the app, occurring in instances where the magnitude of loads were adjusted and the model was simulated again or when interacting with a specific model. Killing the app (by swiping up on the iOS tablet) and reopening it rectified this. Participants mentioned several changes they would implement in the app, such as moving the location of buttons to allow for more streamlined use, adding an axis system, including a scale to illustrate how deformations compared to the predeformed structure, changing the contour map to reflect compression and tension more accurately, and dynamically increasing the load magnitude and observing how the change in magnitude impacts results.

Conclusion

Students often struggle with conceptualizing complex three-dimensional behavior in traditional mechanics-oriented classes. Although structural analysis software is often introduced and taught in these classes to explain these concepts, fundamental behaviors such as elastic buckling, critical locations of maximum stress, and 3D representations of components are still difficult to visualize and learners are unable to interact with these tools. While augmented and virtual reality tools exist that assist with these concepts, these tools are limited, as they require users to have a marker to utilize them or be in a physical location.

This project leverages STRUCT-AR, previously introduced in [13] and [14] and applies it to a pilot study for undergraduate and graduate students who have previously taken an introductory structural system design course. Two graduate students and three undergraduate student interacted with the app on an iOS tablet. The participants then filled out the IBM Post-Study System Usability Questionnaire and an interview where long-form answers could be provided. Participants had overall positive experiences with the app, such as increased engagement, and could use STRUCT-AR to complete the required tasks, but the majority of participants had difficulties using the app without initial instructions. During the interviews, all participants mentioned that a tutorial within the app would have helped their initial exploration, as the current screen after selecting the intended model is the rear camera view with no explanation on where to place the ground plane or how to locate the model. Participants also mentioned how a coordinate system should be implemented in the app, as it was difficult to identify the x, y, z plane relative to the structure. These new implementations will be integrated and tested in a future pilot study before classroom integration in the Fall of 2024.

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