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In-Situ Bending Moment Visualization of a Structure Using Augmented Reality and Real-Time Object Detection

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Abstract

A critical learning outcome of undergraduate engineering mechanics courses is the ability to understand how a structure's internal forces and bending moment will change in response to static and dynamic loads. One of the major challenges associated with both teaching and learning these concepts is the invisible nature of the internal effects. Although concentrated forces applied to the top of the beam can be easily visualized, observing the corresponding changes in the shear and bending moment diagrams is not a trivial task. Nonetheless, proficiency in this concept is vital for students to succeed in subsequent mechanics courses and, ultimately, as a professional practitioner.

One promising technology that can enable students to see the invisible internal effects is augmented reality (AR), where virtual or digital objects can be seen through a device such as a smart phone or headset. This paper describes the proof-of-concept development of a Unity®-based AR application called "AR Stairs" that allows students to visualize (in-situ) the relative magnitude of the internal bending moment in an actual structure. The app is specifically tailored to an existing 40-foot long, 16-foot-high steel staircase structure located at the authors' institution. This paper details the application design, analysis assumptions, calculations, technical challenges encountered, development environment, and content development. The key features of the app are discussed, which include: (a) coordinate system identification and placement, (b) automatic mapping of a stairs model in-situ, (c) creation of a virtual 2-dimensional staircase model, (d) object detection and tracking of people moving on the stairs, (e) image recognition to approximate people's weight, (f) overlays of virtual force vectors onto moving people, and (g) use of a chromatic scale to visually convey the relative intensity of the internal bending moment at nodes spaced over the length of the structure.

It is the authors' intention to also provide the reader with an overall picture of the resources needed to develop AR applications for use in pedagogical settings, the design decision tradeoffs, and practical issues related to deployment. As AR technologies continually improve, they are expected to become an integral part of the pedagogical toolset used by engineering educators to improve the quality of education delivered to engineering students.

Keywords

Augmented reality; beam; mechanics; structural analysis; technology

1. Introduction

Augmented reality and virtual reality (AR and VR, respectively) are growing technologies that allow users to visualize virtual or digital objects through a device such as a smart phone or headset [1]. For engineering educators, the motivation to develop AR content for their curriculum is most often in the pursuit of a tool that helps their students visualize abstract concepts [2-4] such as forces [5], molecules [6], electrical charges [7], and their impact on real systems. In a civil or mechanical engineering setting, AR shows promise as a tool to enable students to visualize force and moment vectors [8]. From a pedagogic perspective, this technology can be seen as an extension of the laboratory that is not confined to a designated space, but can be portable [3].

Since AR technology for engineering education is still in its infancy, these educational tools are not widely available. As a result, AR apps are often designed, developed, and deployed by the engineering educators themselves. The effort required can be overwhelming for educators who possess minimal to no formal training or experience in software development [3]. A recent review of the state of AR in engineering education reported on several aspects of this technology, including (a) the engineering disciplines in which it is utilized, (b) the type of setting, (c) evaluation methods, (d) available features, and (e) interactivity [9]. That review found that more than half of the AR applications (or "apps") focused on technical drawing and electronics and are typically deployed in laboratory settings. Structural analysis, the topic of this paper, falls in the category of construction with fewer studies available. While AR is used to improve student learning of foundational concepts in early engineering coursework, its implementation also prepares students for a future in which AR is embedded in professional settings [10].

One of the major challenges of teaching solid mechanics is to enable students to visualize phenomena that are invisible. Among them include force vectors, moment vectors, as well as their variation throughout a structural member [11]. While these concepts are not considered complex to a seasoned engineering educator, undergraduate students often struggle to learn them. Nevertheless, students' proficiency is fundamental and necessary for subsequent study in mechanics. Among the most important topics includes the internal effects in beams: axial force, shear force, and bending moment. The latter (bending moment) is the subject of this paper. From the authors' experience, students face difficulty when learning the fundamental concepts of bending moment for a few reasons. First, bending moment is inanimate and, thus, students cannot visualize it. Moreover, students can rarely detect any noticeable bending deformation in actual structures due to their large stiffness. The absence of such visible evidence suggests to students that bending moment does not exist. This notion seems consistent with the views of Steif and Dollar, who advise that "*... limiting Statics to rigid, unmoving bodies, hampers student learning*" [12]. Next, some students believe that the bending moment will change in a manner similar to the shear force. More specifically, students assume that bending moment will exhibit only an abrupt change (or discontinuity) at the finite point where a concentrated force is applied. They often fail to recognize that bending moment will vary continuously throughout the structural member despite being subjected to only a single force.

In combination with carefully crafted student-centered activities, AR technology has the ability to dispel those misbeliefs. In a manner similar to that shown in the aforementioned study [12], AR enables students to (a) become active participants in the activity and (b) visualize inanimate phenomena and the corresponding changes in response to participants' actions. This approach was utilized by the authors of the learning tool described herein. The authors present the proof-of-concept development of a Unity®-based AR application called "AR Stairs" [13]. The app enables students to visualize (in-situ) the relative intensity of the internal bending moment in an actual structure (staircase) due to moving vertical loads created by the weight of people walking up and down the stairs. The aim is to bridge the gap caused by student's inability to transfer conceptual knowledge of discrete member analysis to real structures with a complex interaction between members. The main sections of this paper correspond to, and follow the same logical order as, the stages of app development. These include: (1) conceptualization, (2) design, (3) development, (4) testing, and (5) deployment. The authors include challenges, design decision trade-offs, practical issues encountered, and plans for future work. It is hoped that the reader will gain a holistic view of the efforts invested to create an AR application for engineering mechanics education.

2. Conceptualization

Motivation and goals

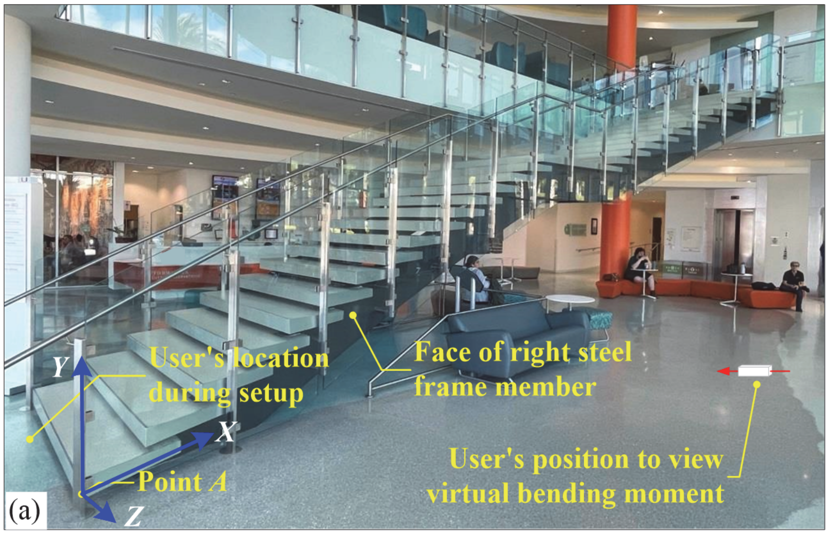
The authors conceived the idea for this app after they developed a prior AR app aimed at helping undergraduate engineering students understand the concept of distributed forces acting on a uniform beam [14]. In that app, students are given the freedom to (a) manually create a virtual beam, (b) specify the locations of a pin and roller support, and (c) apply vertical forces using either a uniform or triangular distribution. The app draws the Free Body Diagram of the beam, displays the resultant force for each distribution, and computes the support reactions. The app was intended to serve as a tool for students enrolled in introductory mechanics (Statics) to learn the basic concept of distributed forces. Since the app did not cover more complex topics related to mechanics and structural analysis, the authors sought to create a new app that was more representative of actual structures and would accomplish the following goals:

- Improve realism by integrating an actual structure into the app
- Incorporate moving live loads instead of static distributed forces
- Engage students as active participants (e.g. the moving loads)
- Compute and display the structure's internal bending moment

Designing the app to be based on an actual structure (in-situ) led to an important design decision trade-off. An actual structure is more realistic, but it is fixed in space and will not permit the user to customize its geometry nor support placement. Furthermore, basing the app on a single structure requires that the entire app design and structural calculations be unique to that structure. Since realism was among the primary goals, the authors opted to use an actual structure.

Setting

The authors selected a 40-foot (12 m) long, 16-foot (5 m) high, 7-foot (2 m) wide steel-framed staircase with concrete steps situated in a student-accessible facility on the main campus of their institution (Figure 1). The staircase consists of two steel frame members; one member is on the left side of the staircase, and the other on the right side. The app performs the structural analysis of the right steel frame member identified in Figure 1(a).



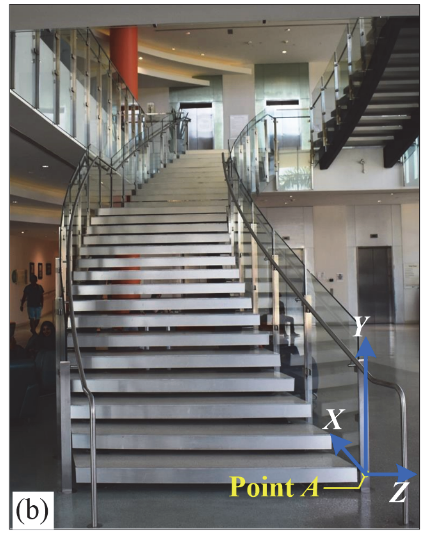


Figure 1. Steel-framed staircase at the authors' institution; (a) isometric and (b) front view

Hardware/platform

A critical decision during the conceptualization stage was to select the type of AR hardware/platform. Two options are typically available: head-mounted display, or a smart device such as a phone or tablet. The decision-making criteria typically includes device availability and affordability. Head-mounted displays, commonly referred to as headsets, tend to be more expensive than smart devices, but they offer more immersivity due to their hands-free capability. The authors opted for Magic Leap One (ML1) headset devices since they were (a) already available from the authors' institution, and (b) technical support staff were well trained to support ML1.

Software

Once the authors selected the hardware/platform, they followed the recommendations of Magic Leap to choose a software, namely, the Unity® game engine and development environment. For the interested reader pursuing other hardware/platforms, ample resources and tutorials are available online to help select a suitable programming environment.

3. Design

This section describes the design process as well as the features of the end product.

Overall process

Design of the app was performed by the authors utilizing a storyboard approach. Storyboarding is the process of creating a visual representation of the user experience, flow, and overall design concept. The authors created drawings and illustrations to help the developers visualize and plan the various elements that would eventually constitute the end product. Storyboards also included annotations indicating the inputs available in each scene, and detailed structural analysis calculations.

User experience

Instructions are conveyed to the user through a series of menus and virtual text instructions, similar to that shown in Figure 2.

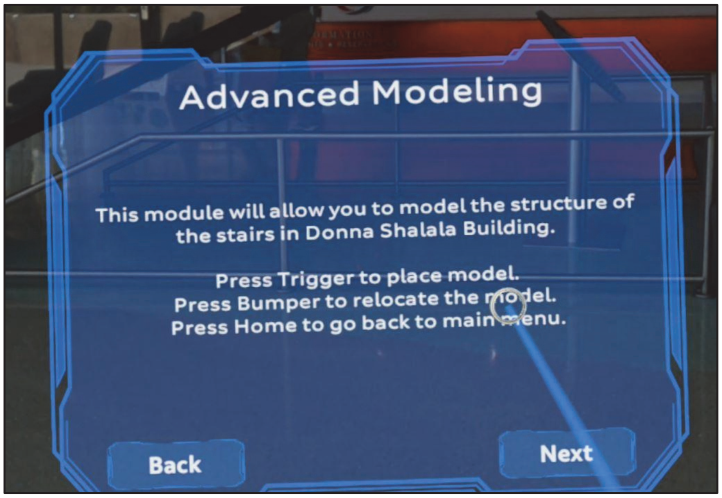


Figure 2. Typical menu and user instructions

When the user clicks the virtual "Next" button using the trigger, a virtual staircase of the same size as the real staircase is shown in the user's field of view. The user then walks to the bottom of the staircase (Figure 3a) and aligns the virtual staircase overlay with the real staircase (Figure 3b). The user presses the Select button on the handset to anchor the virtual staircase at that location.

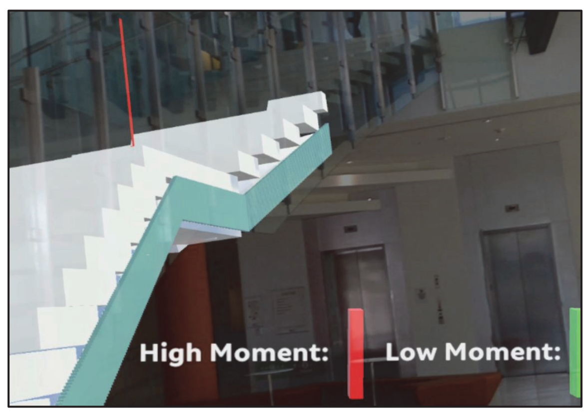
(a)  (b) 

Figure 3. (a) User at the base of the stairs to anchor its position; (b) virtual staircase superimposed onto real one

To provide the user with the best viewing angle and overall experience, the user then moves to a virtual white prism located a few feet from the right side of the staircase. The user faces the staircase in the direction of the arrow (Figure 4). The user is now a passive observer.

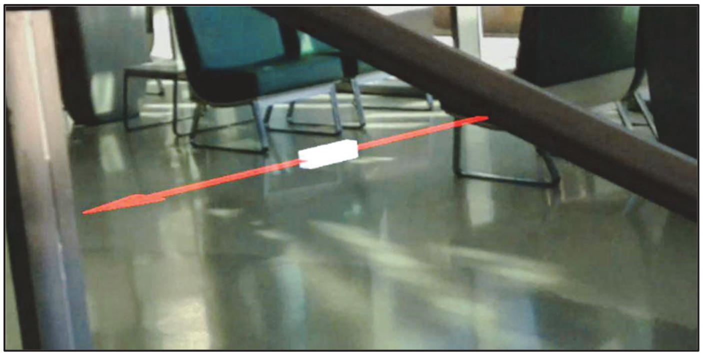


Figure 4. Virtual landmark for user's position and viewing direction

The user presses the Select button on their handset to connect to an image recognition server housed in an on-campus facility. The image recognition algorithm is then initiated, and continuously searches the staircase environment for stationary and moving people. Once identified, their position and approximate height are continually tracked and transmitted back to the headset in real-time. Vertical red arrows are then overlaid onto each person to represent their weight vector. Simultaneously, the app performs the structural analysis to determine the external reactions and internal bending moment throughout the staircase at 483 finite locations. The magnitude of the bending moment at any of the 483 locations (relative to the maximum and minimum values) is displayed to the user using the colored overlay, as shown in Figure 5. The user can press the Menu button on their handset at any time to exit the app.

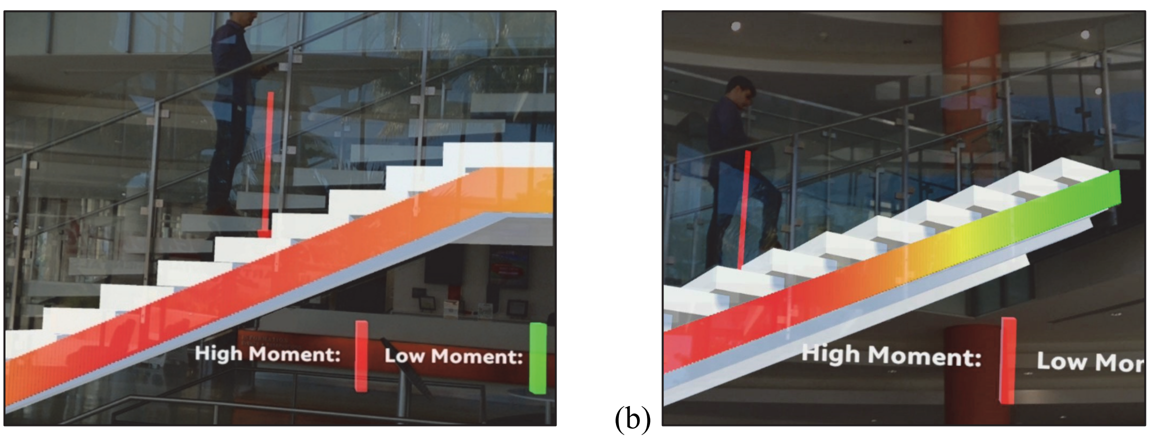
(a)  (b)

Figure 5. User's view of virtual overlays on staircase: (a) vertical force vector representing the person weight; (b) full color palette showing relative intensity of internal bending moment

4. Development

Intellectual resources

Since the two engineering faculty authors are not skilled content developers, the coding was performed by the fourth author as well as a team of certified Unity® developers lead by the third author. Prior to any content development, the students were trained for three months through an on-campus apprenticeship program sponsored by the author's institution. Training included synchronous learning, workshops, webinars, and projects supervised by AR staff experts.

The undergraduate students involved in the development of this structural analysis app had backgrounds in computer science, physics, and electrical engineering. Their unique education allowed them to provide alternative perspectives and suggestions that were not otherwise obvious to the faculty authors. In addition, this project provided the student developers with mentorship from engineering faculty, professional development skills, knowledge of engineering mechanics, and valuable experience in an actual content development environment. While engaging students in the content development was beneficial, it also brought a unique set of challenges to the project. First, the engineering faculty authors had to invest substantial time to educate those content developers who did not have any prior knowledge of engineering mechanics. Second, the transient nature of undergraduate students meant they would depart the project if their course load was too heavy or upon graduation. To overcome this challenge, the development team actively monitored and documented the students' programming decisions and coding logic.

Development environment

App development was accomplished using Unity® version 2020.3.18f1 customized with the Magic Leap package installed, C#, and Visual Studio 19 for the scripts (programs), and Magic Leap's proprietary Lumin OS (operating system) version 0.98.33. Unity® is a real-time cross-platform game engine that is a development environment designed to create interactive content including video games and augmented reality experiences [15]. It handles all aspects of rendering a series of images following the user's actions while automatically tracking conditions such as lighting and physics. Unity® projects are driven by Scenes that contain GameObjects, which are its fundamental building blocks. A Scene is what the user sees and is defined by the camera and directional light GameObjects. Each GameObject has a component menu which describes its properties and behaviors. As shown in Figure 6, the Unity® editor interface consists of five main sections:

1. Hierarchy window (how scenes are related to each other)
1. Scene and Game view window
2. Project window (where assets, scripts, and packages can be accessed)
3. Inspector window (where component menus settings are displayed and edited)
4. Menus toolbar

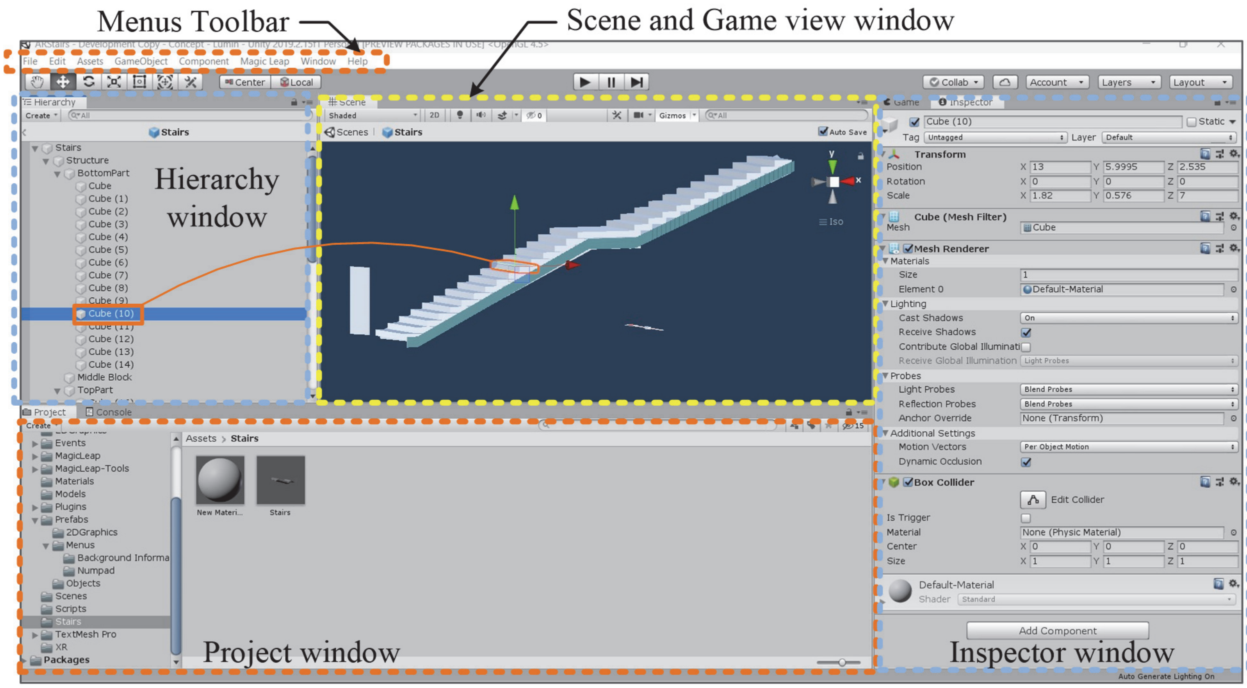


Figure 6. Unity® editor interface

Notice in Figure 6 that each step is modeled as an individual cube. While the app uses a 3-dimensional virtual representation of the staircase as a GameObject, all structural analysis calculations are performed on a 2-dimensional representation of the staircase as a simply-supported frame member.

<u>Image recognition and height approximation of people</u>

Two key requirements are associated with the analysis of moving people on an actual structure. First, the app requires the ability to track people moving up and down the staircase. Second, it is necessary that the app be able to align and overlay virtual objects onto the fixed structure. The authors hypothesized that both necessities could be accomplished using artificial intelligence (AI) for image recognition to detect the loads (people) and their location in real-time. This avoids the use of manual placement by the user or using fiducial (fixed location) markers. In AR, markers are a specific graphical pattern that, when placed in the field of view of the device, act as a tool to identify and understand the real space and trigger a response [16].

The authors considered several machine learning object detection models, each with varying capabilities [17]. Among those to achieve near real-time detection rates is region-based convolutional neural networks (R-CNNs) [18], followed by Single Shot Detector (SSD) [19], and Feature Pyramid Networks (FRN) [20]. To assess their performance, typical metrics include:

1. Speed, measured in frames per second (FPS)
2. Accuracy, measured in mean average precision (mAP) [21]

Since more speed generally implies less accuracy, a tradeoff is required when selecting a model. Recognition of people on the staircase was accomplished using the machine learning object detection model known as Tiny-YOLO (You Only Look Once) Redmon, et al. [22]. While Tiny-YOLO has less accuracy, it possesses the speed needed for real-time object recognition.

As shown earlier in Figure 4, the user stands at the virtual landmark and is oriented perpendicular to the face of the right steel frame member. Real time images are captured at a rate of 10 frames per second through the headset's camera. The images are sent through a wireless internet connection to an NVIDIA Jetson AI (artificial intelligence) server running a deep neural network (DNN) located in the Department of Electrical and Computer Engineering at the authors' institution. The image is processed and objects are identified using Tiny-YOLO. As shown in Figure 7, the detection model creates a two-dimensional virtual rectangular box that represents an envelope in which the moving object (a person) is within.

Figure 7. Two-dimensional box in which the moving person is within

The box is characterized using four pairs of coordinates, each pair corresponding to one corner of the virtual box. Based on the coordinates of the four corners, the height, width, and area centroid of the box are calculated. The person's weight, F_i, is approximated using the height of the box, h_i. Weight is assumed to be directly proportional to the height of the box (not the actual person). A height of 0 inches corresponds to 0 pounds, and 60 inches corresponds to 200 pounds. The value of 60 inches accounts for the model's truncation of the person's height around mid-shin, as shown in Figure 7. Equation (1) presents the relationship between weight and height in US units, while Equation (2) is the SI equivalent with force in Newtons and height in meters.

$$F_i = \left(3.33\frac{\text{lbs}}{\text{in}}\right)(h_i) \tag{1}$$

$$F_i = \left(584\frac{\text{N}}{\text{m}}\right)(h_i) \tag{2}$$

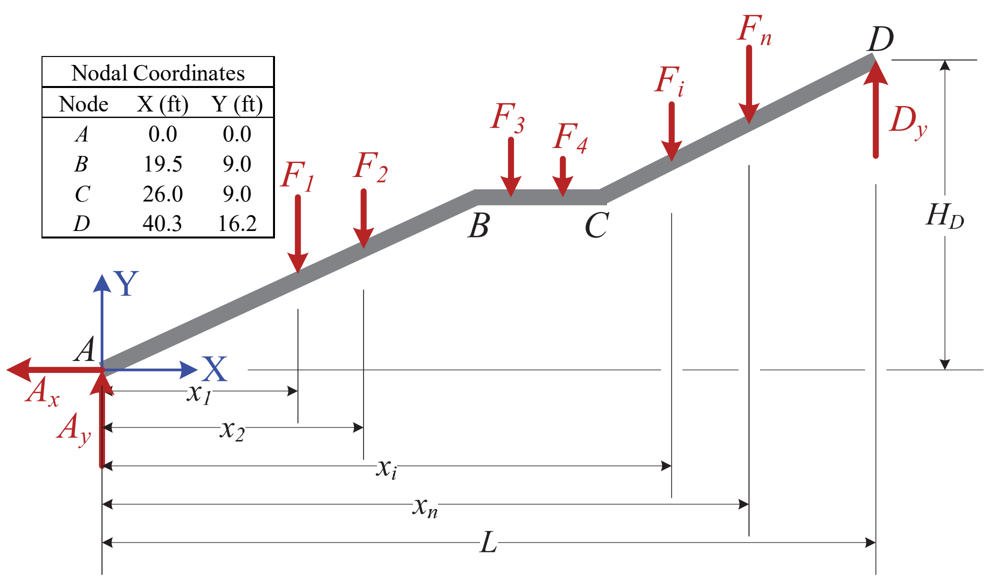
The horizontal distance to the centroidal location of the box's area is assumed to represent the horizontal centroidal distance of the three-dimensional person. Therefore, the centroid represents the location of the line of action of the person's weight vector. The app overlays a downward vertical red arrow at that location. This provides the user with visual feedback that confirms the presence and instantaneous location of a person on the staircase. For sensitivity reasons, the assumed height, centroid, and weight of the people on the staircase are not displayed to the user.

<u>Structural analysis</u>

Since the intent was to demonstrate a proof-of-concept, the authors simplified the analysis and subsequent coding of the app by assuming the following structural conditions:

1. Applied forces resisted only by the right steel frame (Figure 1a)
2. Planar structure (X-Y) with in-plane bending
3. Simply-supported restraint conditions (pin at *A*, roller at *D*)
4. Structure weight neglected
5. Horizontal (X) forces are negligible
6. Since the people being tracked must be near the railing to be detected, their weights are resisted solely by the right steel frame member.

Figure 8 shows the Free Body Diagram of the simply-supported structure used for calculations and analysis. The coordinate system was placed on the right steel frame member at the base of the staircase (point *A*), as shown earlier in Figure 1(a).



Nodal Coordinates		
Node	X (ft)	Y (ft)
A	0.0	0.0
B	19.5	9.0
C	26.0	9.0
D	40.3	16.2

Figure 8. Free Body Diagram of the staircase

The parameters include:

H_D = total vertical height of the staircase (16.2 feet, or 4.9 m)

$i =$ integer index value ranging from 1 to n
$L =$ total horizontal length of the staircase (40.3 feet, or 12.3 m)
$n =$ total number of people on the staircase at any given time
$x =$ continuous variable representing horizontal distance measured from point A
$A_x =$ horizontal force reaction at point A
$A_y =$ vertical force reaction at point A
$D_y =$ vertical force reaction at point D
$F_i =$ vertical force due to the weight of the i^{th} person on the staircase

All calculations are performed *continuously* (10 frames per second) as the loading on the structure is changing. The vertical reaction, D_y, is computed by applying the moment equilibrium equation about point A:

$$D_y = \frac{\left(\sum_{i=1}^{i=n} F_i x_i \right)}{L} \tag{3}$$

Equation (4) is the application of the force equilibrium equation in the vertical direction, which yields the vertical reaction, A_y.

$$A_y = \left(\sum_{i=1}^{i=n} F_i \right) - \frac{\left(\sum_{i=1}^{i=n} F_i x_i \right)}{L} \tag{4}$$

Horizontal loads are neglected and, thus, applying the force equilibrium equation in the horizontal direction produces A_x=0.

Although internal bending moment is a continuous variable for this structure and loading conditions, the authors utilized an approximation by calculating the moment at 1-inch (2.54 cm) finite elements starting at point A. The parameter, a, represents the distance from point A to an imaginary cut in the staircase corresponding to the location where the bending moment is calculated. Since the structure is 40.3 feet (483 inches) long, the moment is calculated at 483 discrete locations, namely, at a =1, 2, 3, ... 483 inches. Figure 9 is the Free Body Diagram of the staircase section to the left of the cut at the arbitrary distance, a. H_a is the height of the staircase at the location of the cut. N_a, V_a, and M_a represent the internal axial force, shear force, and bending moment, respectively.

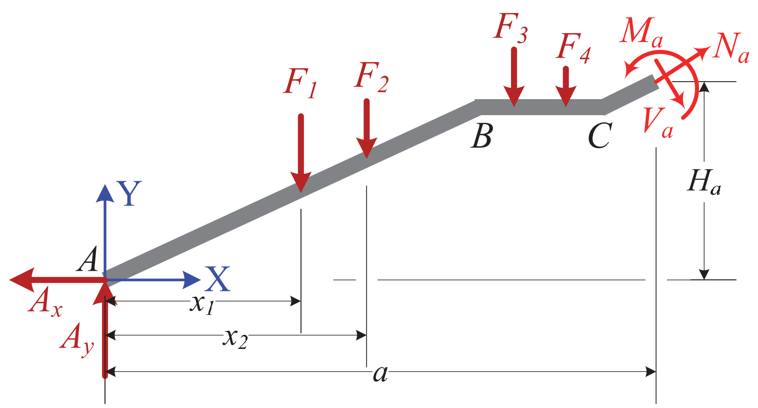


Figure 9. Free Body Diagram of the staircase section to the left of the cut at distance, *a*

The internal bending moment is calculated in Equation (5) using moment summation about the cut.

$$M_a = A_y(a) - \left(\sum_{i=1}^{(x_i<a)} F_i(a - x_i) \right) + A_x H_a \tag{5}$$

The maximum and minimum moment values are then determined for the present (instantaneous) loading condition. At each discrete value of *a* along the horizontal length of the staircase, M_a is compared to the maximum and minimum values. At each location, the moment is assigned a color using 483 fractals that range from red (maximum moment) to green (minimum moment); orange is the average moment. The colors are then virtually overlaid along the face of the right steel frame member.

5. Testing

A number of issues and limitations were identified by the authors while testing the app for several weeks. Nearly all of these challenges were related to the practicality and implementation of the image detection model. These are discussed in Table 1 along with corresponding recommendations or corrective actions taken by the authors to improve the app.

Table 1. Challenges identified during testing, and associated remedies

Issue or limitation	**Recommendation or action taken**
Image detection is unsuccessful when many people are moving on the staircase simultaneously.	Practically speaking, the image detection model can successfully recognize and process up to three people (n = 3) walking on the staircase simultaneously.
	Adequate separation should be provided between moving people. The authors recommend at least 3 feet (1 m).

Based on the user's position and field of view, people standing near the middle of the steps (-Z direction) are not consistently recognized by the model.	Each person being tracked must stand close to the right edge of the staircase (i.e. railing).
Image detection was temporarily disrupted or misinterpreted (e.g. artifacts) due to glare and reflections created on the glass panes on the edge of the staircase.	The effects of the reflections can be reduced if: (a) people on the staircase wear darker-colored garments, (b) direct sunlight is avoided during app usage, and (c) interior lighting is minimal.
Using Tiny-YOLO, some lag was observed in the timing of people on the staircase and the apps' corresponding placement of the vertical weight vector marker.	If feasible, multiple image detection models should be considered.
The interior dimensions of the room relative to the placement of the staircase limited how far from the side of the staircase the user could stand. This meant that the field of view of the user and, thus, the app, was restricted to only a portion of the staircase and never the entire structure.	If feasible, the structure of interest should have ample space surrounding it to provide a wide field of view for the user.
If a person on the staircase had been recognized and the user then changed their head pose, the person would no longer be detected by the model. Accordingly, the person on the staircase no longer had an effect on the internal bending moment.	Users must maintain a wide and consistent field-of-view of the staircase by avoiding positional changes of their body and head.

6. Deployment

The app is designed for single user mode using the specific structure identified. Though functional, the app cannot be deployed in a classroom setting. Instead, each student can individually reserve an AR headset and take it to the location to investigate the structural analysis of the staircase using the app. However, this approach is not conducive to a methodical assessment of the effectiveness of the app and the technology. An alternative is to stream the app in real-time to an on-campus network that students can access in a classroom to watch. It may also be possible to stream the experience to a website that anyone can access. While not as immersive as an individual hands-on experience, it would allow many students to visualize the effects of the app.

7. Conclusions

This paper discussed the stages and challenges associated with the successful development of an augmented reality app that enables students to visualize the relative bending moment in an actual steel-framed structure in-situ due to moving loads (people). Two critical design trade-off decisions were encountered: (1) selecting the type of hardware (immersive nature of headsets versus the collaborative spirit of smart devices), and (2) choosing an appropriate object detection model. Magic Leap One (ML1) headsets were selected as the hardware, while Unity® was chosen as the game engine and development environment. The machine learning object detection model Tiny-YOLO was chosen to recognize, track, and estimate the weight of people moving on the staircase.

A simplified structural analysis of the staircase is performed within the app at a rate of 10 frames per second, and the relative internal bending moment is displayed to the user using a virtual chromatic scale ranging from red (maximum moment) to green (minimum moment). Testing of the app revealed several challenges related to the practicality and implementation of the Tiny-YOLO detection model. The authors conclude that:

- Image detection is improved if at least 3 feet (1 m) of separation is maintained between people on the staircase, and no more than three people are on the staircase simultaneously at any given time.
- Users should maintain a wide field-of-view and consistent head pose to increase the accuracy of the image detection.
- Lighting effects such as glare and reflections disrupt the accurate detection of people on the staircase. People wearing darker colored clothing were better recognized by the model.

The area of AR for engineering mechanics education is rich with possibilities, ranging from basic vector visualization to in-situ analysis of structures. Ultimately, AR apps may offer students a better visualization of engineering mechanics concepts than traditional textbooks. At present, the primary barriers to the widespread adoption of AR technology in the classroom are device compatibility, lack of uniform standards, and limited access for students and instructors.

8. Future work

Continued work on the app may include both technical and evaluative aspects. In terms of technical enhancements, the following elements will be considered:

(a) automatic recognition of the environment such that virtual elements such as the staircase snaps into place without the need for initial placement by the user
(b) guided audio instructions as a means of scaffolding instruction
(c) interactive in-app lessons to test user knowledge
(d) scale-up for larger applications such as dynamic loads on highway bridges

Given the rapid advancement of artificial intelligence and augmented reality technology, the authors anticipate that image detection could eventually be accomplished within the device itself, eliminating the need to connect to a server.

Formal assessment of the app's pedagogical effectiveness [23] and usability [24] is conducive to a mixed methods approach. The authors have already secured Institutional Review Board (IRB) approval to conduct the following:

Quantitative: Student understanding and knowledge retention can be quantified using a quasi-experimental nonequivalent groups design with pre-and post-testing [25]. This can be carried out in Statics, Mechanics of Materials, and Structural Analysis courses.

Qualitative: (a) interviews and focus groups can solicit students' overall evaluation of the app, as well as specific feedback to make technical changes; (b) questionnaires can assess factors such as the quality of experience (QoE) [26] and usability design [27]; (c) assessing changes in motivation and cognitive load can be accomplished using the Instructional Materials Motivation Survey (IMMS) [28] and a cognitive load instrument [29], respectively.

9. Acknowledgements

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