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Mobile augmented reality for teaching structural analysis

Yelda Turkan[a,*], Rafael Radkowski[b], Aliye Karabulut-Ilgu[c], Amir H. Behzadan[d], An Chen[c]

[a] School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331, USA
[b] Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, USA
[c] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, 50011, USA
[d] Department of Construction Science, Texas A & M University, College Station, TX 77843, USA

A B S T R A C T

Structural analysis is an introductory core course that is taught in every civil engineering program as well as in most architectural and construction engineering programs. Previous research unveils students' deficits in understanding the behavior of structural elements in a three-dimensional (3D) context due to the shortcomings of traditional lecturing approaches, which put too much emphasis on the analysis of individual structural members, thereby falling short in providing a solid, easy-to-follow, and holistic approach to analyzing complex structures with a large number of interconnected elements. In this paper, the authors introduce a new pedagogy for teaching structural analysis that incorporates mobile augmented reality (AR) and interactive 3D visualization technology. The goal of this study is to enhance the contents used in structural analysis textbooks and on worksheets by visualizing discrete structural members employing AR along with interactive 3D models in order to illustrate how the structures behave under different loading conditions. Students can interactively change the load and observe the reaction resulting from this change with the instant feedback provided by the AR interface. The feasibility of AR concepts and interaction metaphors, as well as the potential of using AR for teaching structural analysis are investigated, specifically by focusing on challenges regarding content integration and interaction. An AR application is designed and developed, and a pilot study is conducted in a junior level structural analysis class to assess the pedagogical impact and the design concepts employed by the AR tool. Control and test groups are deployed, and students' performance is measured using pre- and post-tests. The results of the pilot study indicate that the utilized AR design concepts have potential to contribute to students' learning by providing interactive and 3D visualization features, which support constructive engagement and retention of information in students.

1. Introduction

Structural Analysis is an introductory core course, which is taught in every undergraduate civil engineering program, as well as in most architectural and construction engineering programs. Structural analysis incorporates applied mechanics, materials science, physics, and mathematics to compute a structure's deformations, internal forces, stresses and strains, and support reactions under external loads [1,2]. Despite its critical role in the curriculum, most students do not appear to have a sound understanding of fundamental concepts such as load effects and load path; and in general, they lack the ability to visualize the deformed shape of simple structures, a necessary skill to comprehend structural behavior beyond theoretical formulae and methods [3–5]. In particular, students have difficulty relating basic structural members including trusses, beams, and frames to more complex structural systems such as buildings and bridges. This deficiency can be largely attributed to the ineffectiveness of the traditional instructional techniques that put much effort on the analysis of discrete members, and less emphasis on understanding the behavior of the entire structure in a three-dimensional (3D) context.

In order to improve students' learning and performance in structural analysis, several approaches have been proposed including the incorporation of physical teaching labs, and cyber teaching tools [1,2,6,7,8]. For example, Davalos et al. [1] developed hands-on laboratory exercises to have students better grasp fundamental structural behavior concepts. Yuan and Teng [2], on the other hand, developed a web-based application for computer-aided learning of structural behavior. More recently, Pena [9] developed a graphical application for tablet computers that supports 2D computer graphics and interaction, which can be used as both a teaching lab module and stand-alone

* Corresponding author.
E-mail addresses: yelda.turkan@oregonstate.edu (Y. Turkan), rafael@iastate.edu (R. Radkowski), aliye@iastate.edu (A. Karabulut-Ilgu), abehzadan@tamu.edu (A.H. Behzadan), achen@iastate.edu (A. Chen).

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instructional tool. There are both advantages and disadvantages to these methods. For the physical teaching lab, it was reported that students could use the laboratory exercise as an efficient vehicle to better grasp fundamental concepts while enjoying the hands-on experiences with structural behavior [1]. However, the cost associated with the development, implementation, maintenance, and staffing, as well as unavailability of space are major impediments to this approach. While flexible and cost-effective graphics-based teaching tools can address the limitations of a physical teaching lab, most existing graphics-based teaching tools still display the content in 2D, i.e. they do not exploit the 3D capabilities and features that allow for better spatial perception. Accordingly, current graphics-based tools hinder the ability of students to fully comprehend the fundamentals of structural analysis and to transfer abstract structural members to real world structures (e.g. simple beams to complex bridge structures).

Although the aforementioned methods can supplement the curriculum and improve teaching and foster learning of structural analysis, little work has been conducted on the instructional delivery aspects, which have remained unchanged for a long time. Previous research has shown that lecturing is not the best teaching approach as it fails to motivate students and provides little, if any, incentive to build on existing knowledge [10,11]. Students join engineering programs because they want to learn how to design and build buildings, towers, bridges, and aircrafts [12]. However, the current engineering education practice does not provide enough opportunities for students to understand their profession on a larger, application-based scale because of the limitations of the traditional teaching methods, the historical disconnects between classroom and the real-life practice, and lack of opportunities for hands-on experiences and collaboration [13].

In order to address these and similar challenges identified in the literature, and building upon previous work, the authors designed and tested a new pedagogy that incorporates mobile augmented reality (AR) and advanced 3D visualization technology for teaching structural analysis. AR superimposes the physical world with virtual 3D information [14–17], a feature facilitating the visualization of structural members that allow students to contextually relate these members to real world structures. This is an important and timely topic because recent technological advancements have made it possible not only to model structures in 3D but also to interact with them in a cost-efficient, risk-free, and accessible manner. 3D design and AR applications have also become the forefront of civil engineering in areas such as 3D Building Information Modeling (BIM) that is rapidly expanding to other domains such as building mechanical, electrical, and plumbing (MEP) systems [18–22], and bridge and road design and inspection [23–29]. Despite such advancements, there is still a major gap between the way structural engineering is taught and the demand from the industry. Thus, it is imperative that existing curriculum be accordingly revised to properly address this gap in knowledge and practice.

The objective of this study is twofold. The first goal is to determine how structural analysis content can be embedded into an AR application. The question is whether the typical, state-of-the-art visualization and interaction concepts deployed in AR yield the anticipated benefits. The second goal is to obtain the students' attitude toward using AR for structural analysis, and to identify the deficits of the application as well as areas of improvement based on students' performance and feedback. In light of this, the focus of this paper is on the design of an interactive AR platform, which is implemented and tested on tablet computers, and used by students in the classroom. In order to help students understand the effect of loads on structures in action, and better relate their abstract classroom knowledge to real world situations, 3D models for selected problems are developed and overlaid on 2D book images. The AR technology is used to enhance the contents of an existing structural analysis textbook by visualizing discrete structural members, and developing 3D animations illustrating how they behave under loading while students interactively change the load that is exerted to the structural members. For example, when working on a problem concerning a beam under loading, students can change the load magnitude as well as the parameters of the virtual beam, and observe how these changes would affect the structural behavior of the beam. The design of the AR platform follows the typical notation and nomenclature used in structural analysis classes as well as the prevalent assumptions of how an AR book solution works best (Section 2.1). These include 3D models allowing students to review the content in 3D and contextually relate it to the physical object of interest, instant feedback, and collaboration. It is assumed that these concepts enable the evaluation of learning benefits in this research since they were introduced and tested in related but different contexts. To assess the pedagogical impact, an experiment is conducted in a junior level structural analysis class at Iowa State University. For this experiment, control and test groups are deployed, and students' performance is measured using pre- and post-tests.

The rest of this paper is organized as follows: the next section provides background information on AR, 3D modeling, and AR applications in Architectural, Engineering, and Construction (AEC) domains as well as in education. Next, technical details of the developed AR tool for structural analysis are presented, followed by a description of the pilot study and its experimental results. Finally, conclusions are drawn and a discussion on future research needs and directions is provided.

2. Background

AR visualization facilitates improved human-computer interaction by superimposing the natural visual perception of a human user with computer-generated information, i.e. 3D models, annotation, and text [14]. In an AR environment, such information is ideally presented in a context-aware way that is appropriate for a specific task and, typically, relative to the user's physical location. The general approach to realize AR is to merge the physical and virtual worlds by exploiting rapid video processing, precise tracking, and computer graphics. In a typical AR system, a video camera is used to capture scenes from the physical surroundings. Because the locations of the camera and the user are known, AR software systems use rapid image-processing techniques to identify one or more markers placed in the scene. Using the optical properties of the cameras, the position and orientation of the markers are then precisely calculated. Given this information, the AR rendering engine enriches raw videos captured from the user's surroundings with computer-generated graphics and ultimately, displays this mixed scene to the user.

AR applications require special display technology to superimpose the physical environment with computer renderings of virtual objects. A typical device is a wearable head mounted display (HMD) such as Microsoft Hololens or Google Glass. The working principle of displays of this type is depicted in Fig. 1. In particular, the display system

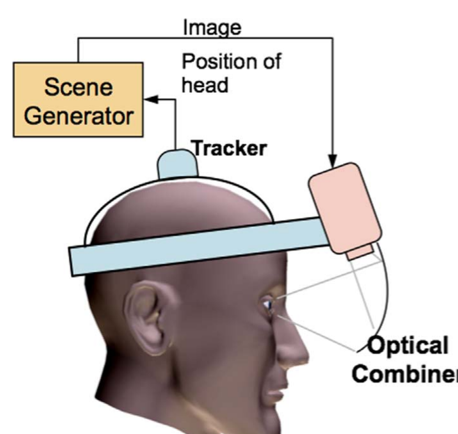

Fig. 1. Work principle of an optical-see-through head mounted display.

incorporates four basic components: an optical combiner (i.e. an optical prism or a semi-transparent mirror), a scene generator, a tracking device, and a projector or display. The role of the tracking device is to compute the current location of the user and its current view direction. Clearly, for an AR application to superimpose the user's perception of the physical environment, it needs to know where the user is located and at which direction he or she is looking. The scene generator then uses this information to create an image from the correct view point and perspective. For this purpose, a microcomputer (or system-on-chip) along with a graphics card is used when the entire computational unit is embedded into the housing of the display device. Nevertheless, tethered devices are still in use and images can also be transferred through a network connection. Subsequently, this image is projected onto the optical combiner, which is usually placed in front of the user's eyes in form of a device such as an eyeglass. The user can then simultaneously observe the physical environment as well as the superimposed virtual objects through the combiner. This generates the perception of virtual objects and physical world coexisting in the same environment.

Although HMD is considered a typical AR display device, currently smartphones, tablet computers, and ordinary computer displays are also employed for AR due to their availability and low cost. However, microelectronics and display technologies are continuously improving which in turn lowers the cost of HMDs. Therefore, an increase in their adoption for AR applications can be expected in the near future, which will most likely replace smartphones and other mobile devices. In the meantime, using smartphones and tablet computers is still an inexpensive and scalable approach to examine the capabilities of AR technology with a large group of students.

In this study, tablet computers, iPads in particular, are used based on the recommendations of the existing literature [30–35], and also given the fact that they are affordable and readily available. Tablet computers as well as smart phones have already been employed in education for a variety of purposes. While the main advantage of smartphones is their availability, the small screen size make them less desirable for applications with emphasis on visualization and interaction, such as the one of this study. On the other hand, tablet computers have larger displays that facilitate better interaction with the virtual content [30,36], which is why tablet computers are ultimately adopted for this study.

As mentioned above, AR visualization relies on tracking, which comprises a set of very different technologies with the goal of determining either the user's head position and viewing direction, or the position of objects in the environment, or both. Existing technologies are plenty and the choice depends on factors such as the number of objects to track, and the desired output accuracy [37,38].

One of the first vision-based AR tracking systems was the ARToolkit [39], which employs fiducial markers. Each marker incorporates a black square and a graphical pattern within the square (Fig. 2). The black square is required to initially find the marker in the captured scene of the real world, and to compute the spatial relation between the

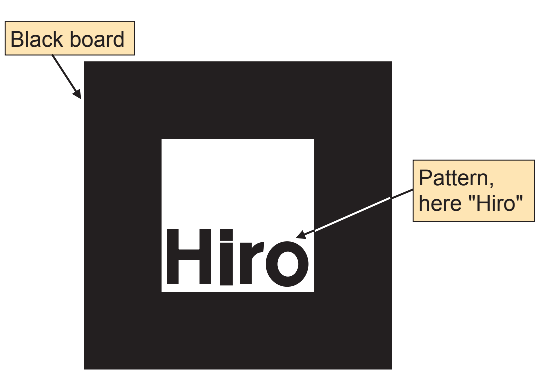

Fig. 2. An ARtoolkit marker.

marker and the camera. The pattern inside the black square is unique to each marker and is thus used to distinguish markers from one another. Several derivatives of the ARToolkit tracking system have been introduced (e.g. ARTag, Studierstube) to address key implementation challenges. Despite its improvements and ease of use, to the authors' best knowledge, ARToolkit has not been widely used in professional applications other than education and game environments.

Another (more sophisticated) tracking technique is feature-based tracking or natural feature-based tracking [40]. If the borders of an ARToolkit marker are considered as artificial features, natural features include all invariant texture patches, color blobs, edges, and corners, which are naturally part of the environment. A detailed review of all computer vision techniques exceeds the scope of this paper. In general, features of an object of interest can be stored as descriptors in a database. The database descriptors are compared with those extracted from a video during runtime. Statistical pattern matching is employed for this task [41,42]. Once a match id found, the position and orientation can be computed and used for AR visualization.

2.1. AR implementation in STEM education

Within the past decade, there has been several attempts at integrating AR into the mainstream of a variety of STEM fields both at the operational and training levels; such as medical training [43], disaster management [44], military training [45], and vocational training [46,47].

Since AR applications support user interaction, provide instant feedback, and are exciting to use, they can potentially foster learning, as indicated in previous studies [32–34]. While the majority of existing efforts have targeted primary and high school education [35], college education is also another niche area of research that is (to a lesser extent) under investigation. Phon et al. [48] published a survey presenting an overview of existing work in this area. In this paper, however, the review of the related literature instead focuses on aspects that are considered key for a successful design and implementation of an AR application, namely, 3D visualization, interaction, collaboration, and instant feedback.

3D visualization within the context of this work refers to the means that enable concepts, data, and instructions to be presented as 3D models rather than 2D sketches. Singhal et al. [32] for instance developed an AR application to foster understanding of chemical elements. The application organized fiducial markers to represent the periodic table. Students could pick a marker and place it over a predetermined location in the table, which would then activate a 3D model of the respective chemical element. This allowed students to explore interactively the element's structure and to better understand how different elements interact with each other considering their spatial structures.

Additionally, a large number of AR Book-like applications have been developed for education and training purposes. The term AR Book [49,50] is generally used to describe a printed book in which the print content is enhanced by being augmented with AR visualizations. A typical printed book solely conveys static information such as charts, tables, and figures. Using AR and a display device, such static illustrations can be superimposed with 3D models, animations, and other forms of multimedia. Kraut and Jeknic [51] for instance focused on vocational training of electrical circuits and developed an application that could augment the images of a book with 3D models and animations explaining the context, and reported positive initial feedback from users. In another study, Bazzaza et al. [52] used a similar approach and enriched the contents of newspapers and books with 3D models with the goal of better conveying the intended information. The user attitude toward the application was reported to be positive. Camba et al. [30], and Buesing and Cook [31] implemented AR to improve teaching engineering graphics and physics courses, and observed a general positive attitude, and a high level of user satisfaction. In summary, the related research reports that using 3D models instead of 2D images to the most extent fosters learning.

Since AR applications are technically categorized as a form of computer visual simulation, they can be further utilized to generate a response to the users' input. Studies indicate that this instant feedback also fosters learning and better engages students. An interesting approach was introduced by Qassem et al. [36] who developed a monitor-based AR application with fiducial markers to teach chemistry by allowing students to combine two or multiple markers, thus, combining two or multiple chemical elements. The application would instantly compute the chemical reaction and show it as an animated 3D model. A similar study was presented in Wojciechowski and Cellary [53]. Enyedy et al. [54] examined the feasibility of using AR to teach young children (6–8 years old) scientific modeling through play. They reported that AR technology helped meaningfully engage children with force and motion concepts despite their young age. There are several other studies that have utilized simulations to provide instant feedback to users. Matcha and Rambli [55] introduced AReX, a study for optics simulations in which students learned about the behavior of light in the presence of simulated lenses. An AR application for logistics training was introduced by Cuendet et al. [56] in which students used physical building blocks to create a warehouse layout. Each block was tracked, which allowed the layout to be replicated in a computer simulation, thus enabling instant feedback and highlighting operational bottlenecks and material flow jams. Results from these studies suggest that instant user feedback is an important factor in an AR application developed specifically for educational purposes.

As previously stated, another key aspect of an AR environment is collaboration, which is commonly known to be a driver of engagement. An early study that assessed collaborative gameplay and AR was conducted by Dunleavy and Dede [57]. In their study, subjects were asked to walk to virtual elements in a collaborative game (Alien Contact) and collaboratively work with them. In another study, Li et al. [58] focused on collaboration and education. They developed and used an AR application to teach physics. They also compared different display devices. Students were asked to collaborate to solve different types of problems. Similar studies from other fields that addressed collaboration in education are introduced in Alhumaidan et al. [59], Matcha and Rambli [60], and Vate-U-Lan [61,62]. Although there is a strong indication that AR applications and their collaborative nature can leverage education, compared to studies in visualization and interaction topics, there is still a dearth in research in collaborative AR implementation for classroom education. Dunleavey and Dede [57] conducted pioneer research in this area. However, the attributes of AR that foster engagement among students are not yet well understood, except for typical game-like features such as ranking lists, shared performance batches, and trophies.

In summary, previous work strongly suggests that three features that foster learning in AR are context-related 3D models, instant feedback, and collaboration. In particular, AR utilizes interactive 3D animations, which are, in comparison to 2D sketches and drawings, vivid and enlightened. They allow for a better comprehension of the related topics, especially when a spatial or temporal understanding of the matter is required. AR applications can also offer instant feedback by employing simulations. It has been demonstrated that instant feedback allows students to better learn the content and to avoid reinforcement of misconceptions. Finally, the advantages of collaborative education and training in a typical classroom are unchallenged and it has been shown that AR encourage collaboration, which promotes learning.

2.2. AR implementation in AEC domain

Within the AEC domain, AR has been implemented to support project planning, design, construction, and maintenance [63]; visualization of construction graphics [64]; creation of virtual immersive jobsites [65,66]; construction defect management [67]; construction site visualization and communication [68]; and damage prevention and maintenance of underground utilities [69,70]. Recent AR applications in the AEC domain have also enhanced performance in areas such as virtual jobsite visits, progress tracking by comparing as-built and as-designed models, improving communication among project stakeholders, and planning and coordination for future projects [71,72]. Examples of such applications include but are not limited to a client/server AR system on mobile phones to view assembly parts [68]; an AR system which combines social media, AR, and 3D modeling for home interior design [73]; an immersive AR model that uses interactive speech and gesture recognition for visualizing and interacting with buildings and their thermal environments [74]; excavator-collision avoidance systems [75]; and visualization of operations-level construction activities [69].

Although these implementations indicate the promising potential of AR to enhance productivity and safety in civil and construction engineering practices, the integration of such technologies into undergraduate teaching has been very limited despite the evidence that it facilitates learning of abstract and difficult-to-understand topics [76]. Researchers predict that AR technologies will be broadly adopted by the industry within the next ten years [17]. Therefore, it is imperative that educators and instructors make it a priority to help students better prepare for the demands of the 21st century industry by giving them the opportunity to transcend the boundaries of traditional learning through seamless integration of advanced technologies that are increasingly gaining traction across many industries and professions.

2.3. Problem description

In this work, several design concepts, namely context-related 3D models, interaction and instant feedback, and collaboration (as described in Sections 2.1 and 2.2) are adopted, incorporated, and tested in the developed AR application. Although the literature provides strong indications pertaining the efficacy of applications following these design principles, previous work also indicate some disagreements and do not completely match with the use case in this study. For instance, some applications have been deemed to generate acceptable output when incorporating 3D models without physical context [32,35], where in contrast, the majority of the studies [51,52,30,31] emphasize the importance of relating 3D models to physical context, i.e. images and physical objects. In addition, instant feedback is considered as encouraging. While the authors do not contradict with this assumption, they noticed that the majority of applications provide simple, binary feedback, e.g. an electrical circuit either works or doesn't. Providing feedback in an AR application used for teaching structural analysis, however, proves to be more complex. A typical structural analysis problem may ask students to calculate reaction forces and deflections, or to determine whether a structure meets design and performance requirements. This implies that the AR application must be also able to provide relevant feedback with the same level of detail. Furthermore, there are other challenges when using AR for teaching structural analysis. For instance, recognizing and understanding angles between structural members are of importance in students' training since designing and implementing a proper structural joint at a certain location entail a particular angle (and thus, design) of connecting members. Typical 2D textbook sketches allow one to recognize these angles and their importance since 2D sketches preserve angles between objects as well as distances, thus students can perceive them. An AR application, however, provides a perspective view since the camera lens can be simulated using a perspective projection. A perspective projection distorts the perception of all angles and distances, thus hindering the ability to thoroughly convey this notion to students. Therefore, there is a major need to verify the commonly accepted AR Book design concepts for structural analysis education.

It is worth mentioning that in this paper, the authors did not see the necessity to compare multiple AR application designs since different visual features and interaction concepts were already investigated in previous studies from several domains. The aim of this study rather is to adopt the “best lessons” from the literature and to verify its practical outcomes.

3. Development of the augmented reality (AR) tool for structural analysis

In this study, a self-developed marker-based AR application is designed for iOS-based tablet systems (iPads). Nevertheless, the same application can be designed and implemented for other tablet computer systems, as the choice of the platform has no impact on the educational content. The developed application uses fiducial template markers to register virtual contents over a video of the real world as observed by users (i.e. students). Building upon the previous work, this study adopts an AR book-like application to foster learning, and is aimed at engaging students by providing them with instant feedback (i.e. load distributions due to exerted forces, which can be modified interactively). This section introduces the application design and the software architecture.

3.1. Application interface design and interaction

Fig. 3 shows the user interface of the designed AR application in this research. As shown in this figure, the application screen follows a typical border layout in landscape orientation with a center area and adjacent borders. The main part of the view is reserved for the superimposed video, further denoted as the AR view. Additional graphical interaction widgets are placed along the borders. The notion behind this layout is to keep a major portion of the view free of clutter, often caused by widgets and other elements. The AR view shows a video image (in the background), which is superimposed with structural analysis content rendered as a virtual object (rendered in the foreground). For this application, the content of interest is displayed as a 3D model of a frame (similar to that shown in Fig. 3), beam, or another type of structural element. All virtual structural members are animated using object morphing (Section 3.3). Thus, each shape reflects its members’ reaction to the current load and frame construction. In addition, 3D arrows are used to indicate the load exerted on the structural elements as well as the reaction forces. For instance, the frame in Fig. 3 is subjected to a uniformly distributed load and a point load, both indicated by arrows. The arrows are animated and their lengths can change to reflect a change in the magnitude of loads, thus allowing the user to obtain a quick overview of the current loading condition. The design follows the common structural analysis notation and nomenclatures (e.g. arrows for loads). Therefore, students do not need to learn new notations, and can still use the ones already learned in the course. The application is

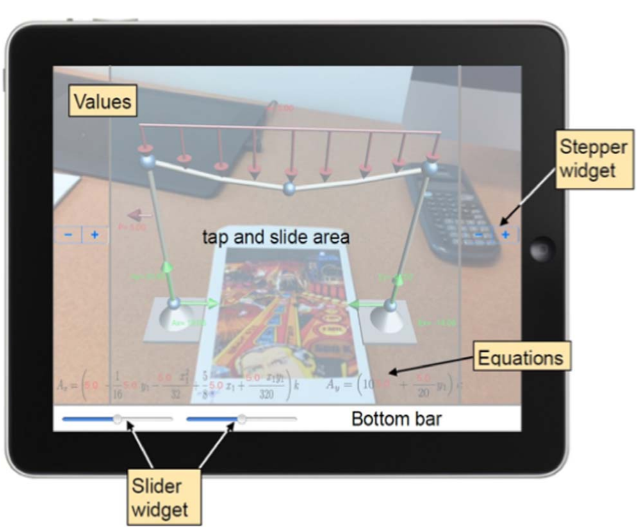

Fig. 3. User interface of the designed AR application.

interactive; the user can and is expected to change the load using stepper and slider widgets. The stepper widgets are placed at the left and right borders of the application view. Users can easily access them in landscape mode with their thumbs when holding the iPad on the left and right border. The steppers allow one to change the load in discrete steps only. All reaction forces as well as deflections of the frame elements are instantly calculated in real-time. Thus, the user sees an immediate response, a function that satisfies the need for instant feedback.

The interaction widgets are hidden from the user in the regular view mode, in which the user only views the result in an uncluttered scene and does not intend to interact (e.g. change the load). To reactivate the stepper elements on the right and left sides, the user must tap the screen once anywhere while in the main view. The stepper elements disappear automatically after a 5-s idle time. Slider widgets, on the other hand, will appear with an upward swipe gesture with two fingers, and a downward swipe gesture hides them again.

The application is locked in landscape orientation since this orientation offers the best view while students are interacting with the scene. A portrait orientation in border layout would further shrink the available view space when placing widgets on left and right borders. As previously mentioned, the designed AR application is marker-based, template markers in particular (see Section 3.4). The 3D models for a particular problem appear when the user places a maker in front of the camera. The interactive interface design follows commonly accepted usability criteria and heuristics [77,78].

3.2. Software architecture

The designed AR application is based on the iOS software development kit (SDK) and follows its prevalent model-view-controller (MVC) architecture model. Fig. 4 shows an overview of the software architecture including all subcomponents and their functions. The main software components are an interface/view component, an application controller, a rendering component, and a tracking component. The interface is mainly implemented using Apple’s Cocoa touch SDK, written in Objective-C. The rendering module is based on OpenGL ES 2.0 and written in C++. The tracking module uses the ARToolkit library and is also implemented in C++. The controller module is implemented using Objective-C as well as C++.

The main function of the *interface/view component* is to maintain data structures and algorithms for all interaction widgets, interaction processing, as well as for the AR view. The widget view is composed of a standard Cocoa *UIViewController* class along with the corresponding *UIView*. All interface widgets are part of the view. The view controller receives events when the user interacts with a widget or invokes a gesture. Each received interaction event is processed, and forwarded to the controller. Following the MVC architecture pattern, no further processing is carried out in the view. The AR view is essentially implemented using the same two mentioned classes, with new instances. However, these instances only act as placeholders allowing access to the underlying graphics resources. The view object especially its resource handle is replaced by an OpenGL handle.

The *controller component* implements the application logic. From the application’s point-of-view, the main task is to manage the computations required to solve the structural analysis problem. In addition, the controller also controls the appearance/disappearance of all widget elements and selects the 3D models that need to be displayed for a given task.

The management process is twofold: first, the controller identifies the current problem and selects the associated equations. Next, it calculates the deflection and reaction forces.

The application can manage multiple structural analysis problems/tasks using a template pattern [79], further denoted as problem template. The problem template basically implements the reaction force equations and deflection calculations. Each structural analysis problem is an instance of a problem template, denoted as problem object, which

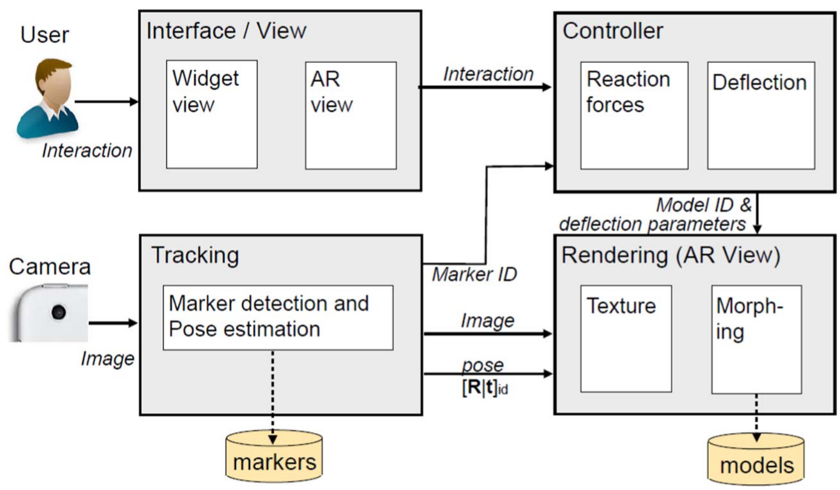

Fig. 4. Software architecture of the designed AR application.

is associated with a unique problem ID. Every problem ID is associated with a marker ID that relates that problem to an AR marker. Given a structural analysis problem, the task of the controller component is to maintain a list with all associations and to activate the problem object when the related marker is visible. Only one problem object, thus, one set of equations can be activated and processed at any given time. Therefore, only one structural analysis problem can be solved at a time. The marker ID is decoupled from the problem ID to prevent sudden problem object swaps. The tracking component sends the marker ID continuously, at each frame in which it detects a marker. Nevertheless, a marker can disappear for one or two frames as a result of random noise, shadows, user interaction, or other events that cause the tracking component to stop submitting the marker ID. Without further insertions, the application would stop processing the current structural analysis problem. To a user, this will visually translate into 3D models starting to flicker on the screen. To bypass this issue, the controller component observes the marker ID and only disables or replaces the subsequent equations when the marker disappears for more than 5 frames.

The second task of the controller component, besides managing equations, is to compute the reaction forces and deflections, as previously described. The reaction force calculation, the equilibrium equations in particular, are currently implemented in C++ and are part of a problem object. The deflection information is pre-computed and loaded from a file (see Section 3.3). A minimum of two models are required for one load: a nominal model of a frame, and a model with maximum deflection for a given load. The nominal model represents a structure under zero loading, and the maximum deflection model represents the same structure under full loading. For any given loading situation, these two models are blended linearly resulting in a blend weight ω to accommodate that particular load situation; the blending is processed by the rendering component. For each additional load, an additional maximum deflection model is required.

The next module is the *tracking component*. As previously noted, the class of AR application used in this research is commonly referred to as marker-based AR, which relies on continuous object tracking (i.e. marker) in video frames. This function is carried out by the tracking component. In particular, this component fetches images captured by the video camera of the iPad, processes them to identify markers, and then calculates the position and orientation of each marker. Subsequently, the marker ID is forwarded to the controller component and the marker pose is sent to the rendering component. Further tracking details are explained in Section 3.4. The largest component of the designed AR application is the *rendering component*. This component generates the AR view, which incorporates the video background and virtual objects. Technically, the video background is implemented as a 2D texture the content of which being the image from the video camera. All 3D objects are rendered into a second image, which is superimposed on the video image. In this research, OpenGL ES 2.0 is used to implement all rendering functionalities.

3.3. Three-dimensional (3D) content and deflection

An important concept to introduce when teaching structural analysis is shape deflection. The shape of each structural member must reflect its response to the current loading condition, which may be very small, and difficult to visualize in some cases. This is why, in this study, the elements' reactions were magnified to provide a clearer view for the students and allow for better visual understanding. This feature is realized using object morphing. The 3D content of the scene consists of a frame model implemented as a morphed triangle mesh. Morphing results in a visual deflection of the 3D model. In the designed application, blend shape morphing is used [80]. Blend shape morphing is an interpolation technique that interpolates the position for each vertex of a triangle model between a nominal model and one or more transformed/morphed models [81]. The basic idea is explained in Fig. 5 for one point of a beam.

In this figure, consider the point $\mathbf{p}_{0,0} \in \mathbb{R}^3$ as a nominal vertex point. The nominal model shows the shape in its original, unloaded situation or under minimal load. A second model shows the model in its maximum deflected situation under full load, with a vertex point $\mathbf{p}_{0,1} \in \mathbb{R}^3$. Each additional model shows another load situation. During application initialization, a delta vector is calculated for each point, given the location in both models $k = 0$ (nominal model) and $k + 1$, as shown in Eq. (1),

$$\Delta p_i = p_{i,0} - p_{i,k} \tag{1}$$

with i, the point index, and k, the index of the deflected models. All

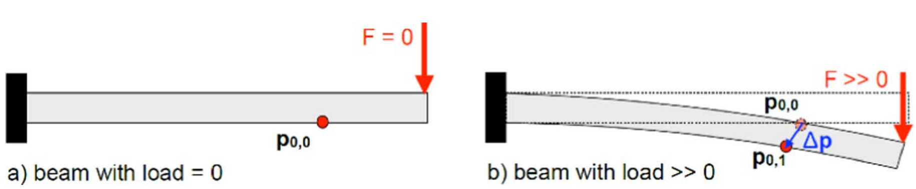

Fig. 5. Blend shape morphing based on difference vectors between (a) nominal, and (b) morphed shapes.

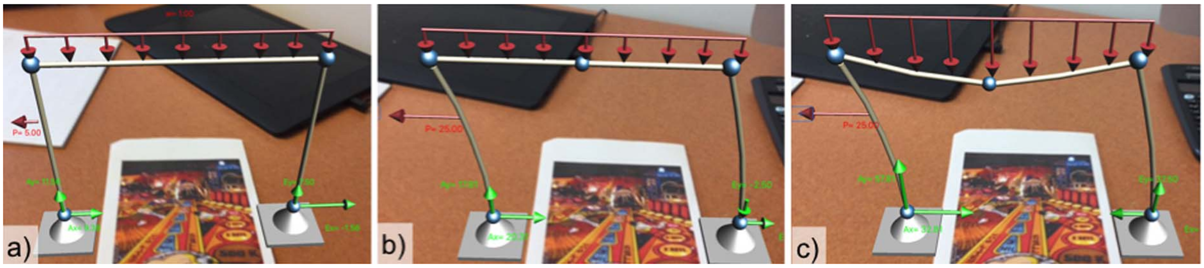

Fig. 6. Blend shape morphing results with different load situations: (a) nominal model, (b) frame subjected to a point load, and (c) frame subjected to a point load and a uniformly distributed load.

models are loaded from .obj files. During runtime, the final, deflected model is calculated for each point i using Eq. (2),

$$p_i = p_{i,0} + \sum_{k=1}^{N} w_k p_i \tag{2}$$

with w_k a weight values ranging from 0 to 1. A changing weight value changes the shape of the final model. A value $w_k = 0$ results in the nominal model, and a value $w_k = 1$ results in the maximal deflected model. The equation to calculate w_k depends on the load situation and the shape of the structural element. In this study, only elastic behavior is considered, and as such, structural deflections are proportional to external loads. For instance, given the loading situation (an axial load P and a uniform load u) applied to the frame shown in Fig. 6, w_k can be expressed using Eq. (3),

$$w_k = \frac{1}{\delta_{max}}\left[\frac{P}{P_{max}}\delta_P + \frac{u}{u_{max}}\delta_u\right] \tag{3}$$

with δ_{max}, the maximum deflection at a point i from model k, δ_p, the current deflection from load P, δ_u, the current deflection from load u, and P_{max}, u_{max}, the maximum forces. The last two are fixed parameters, which are calculated using structural analysis methods. The weight value obtained from Eq. (3) is calculated separately for the x- and y-directions. This calculation is also part of the controller component.

Results are shown in Fig. 6. Fig. 6(a) is the nominal model, Fig. 6(b) is the morphed model with a maximal load P, and Fig. 6(c) adds the uniform load u to the point load P. Although the situation shown in Fig. 6(b) only needs one blended model, the situation in Fig. 6(c) requires to gradually blend two models with a nominal model when the forces increase.

Although blend shape morphing is an easy-to-use technique, which facilitates real-time rendering, a disadvantage of this method is its dependency on known point associations between models. The method essentially requires a constant number of vertex points during the entire morphing process, thus, the overall shape of an object must remain somehow unchanged. Having said that, for the intended purpose of the designed application (visualizing small structural deflections), blend shape morphing is deemed suitable since only slight changes in the shape of the structural element are expected.

Note that the deflection for the entire frame was pre-calculated using analytical equations verified by Finite Element analysis. For each frame element, the deflection under full load was calculated in discrete steps using the equations. The step size was based on the increment of the loads. The deflection values were stored in list format in an ASCII file in .csv format where the location of the value in the list corresponds with the distance along the frame segment. Since the general dimension of the frame elements do not change, there is no reason to compute the basic deflection online. The developed AR application loads the file content via the C++ standard template library input/output (I/O) interface and stores it in an array.

3.4. Object tracking in AR application

Generally, there are two different object-tracking solutions that can be adopted for AR Book applications: marker-based tracking and feature-based tracking. Feature-based tracking works with natural features (e.g. edges, color blobs, texture patches), where, from a technology point-of-view, markers are considered as artificial features, concrete geometric shapes such as boxes and frames. In this study, the objects that needed to be recognized and tracked are textbook pages and problem sheets embedding pictures and text. Therefore, a feature-based tracking (see Fig. 6) was initially considered. A feasibility test, however, quickly revealed that typical textbook pages cannot be recognized and tracked very well using this approach due to the presence of thin lines in a typical printed figure, slightly folded pages, tables of different sizes and styles, and students' handwritten remarks. In particular, state-of-the-art approaches [84] as well as sophisticated computer vision techniques [85,86] could barely recognize thin-lined sketches. Therefore, feature-based tracking option was eventually ruled out for not being a reliable solution for this study, and marker-based tracking was adopted. Unlike natural features, markers can be easily generated and embedded into a problem sheet, and marker detection and tracking is more reliable compared to feature-based tracking.

As discussed earlier, marker-based AR relies on tracking which means identifying an object (i.e. an AR marker) and calculating its pose (position and orientation) in the image with respect to the camera, for each video frame. The position and orientation information enables the alignment of a virtual object with the physical object, which is ultimately shown in the video image, thus giving a user the impression that the virtual object is blended into the physical world. In this research, ARToolkit is used for object identification and pose estimation [39]. The ARToolkit built-in library returns the ID of each identified marker along with its pose as a transformation matrix $[\mathbf{R}|\mathbf{t}]$ in a homogenous coordinate system. In this way, more than one marker can be tracked at any time, with the maximum number governed by the CPU processing power.

Additionally, in the presented work, a multi-marker tracking approach is adopted to increase robustness. A multi-marker combines several physical markers into one logical marker. To maintain tracking, ARToolkit must detect at least one marker in the video image. Occasionally, a user may unintentionally cover one or more markers when using the application or moving around the sheets of paper (on which markers are printed). Using more than one marker in a multi-marker approach increases the chance that at least one marker always remains visible, thus guaranteeing robustness of the marker tracking process. In the experiments conducted in this research using structural analysis problems, markers are placed at the corners and/or borders of the paper that the students receive (Fig. 7). A marker ID is associated with each structural analysis problem or vice versa, every structural analysis problem is associated with one logical marker. As soon as the ARToolkit detects this marker, it sends its ID to the controller component, which automatically selects the proper models, the interaction widgets, and the reaction force equations. If two or more multi-marker sets are in the field-of-view, ARToolkit will report all of them to the controller component.

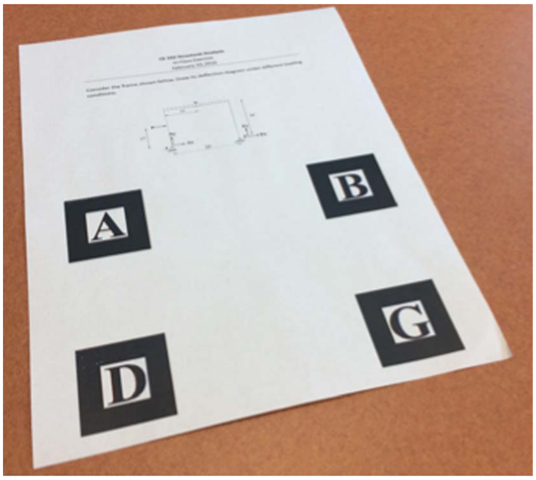

Fig. 7. ARToolkit multi-marker sets are used to increase the tracking robustness.

4. Pilot study: assessment of the augmented reality (AR) application

The designed AR tool is piloted in a junior-level structural analysis course to measure student learning outcomes as well as students' attitude toward using the AR interface design concepts. The goal of the pilot study is to investigate two questions: (1) does AR effectively incorporate the three aforementioned interface design concepts in learning structural analysis? and (2) what are students' perspectives on the use of AR for learning structural analysis?

4.1. Research context

The designed AR application was piloted in the Structural Analysis course (CE332) offered to civil and construction engineering students at Iowa State University. Approximately, 1000 students are enrolled in the department. CE332 is a three-credit hour junior-level course in which students learn how to analyze forces and displacements for determinate and indeterminate structures using both equilibrium and energy-based solutions. Structural types include beams, frames and trusses. Loads include vertical (gravity) and lateral forces (wind or seismic) as well as settlement, tolerance and temperature-induced displacements. Structural Analysis is a prerequisite course for several other design courses in structural engineering, including Structural Steel Design (CE333), Reinforced Concrete Design (CE334), and Capstone Design project (CE485). In addition to the three contact hours with the main course instructor, students attend an optional, one-hour-long recitation session led by a graduate teaching assistant. During recitation, teaching assistants solve example problems to recap what has been covered in the lecture as well as answering questions about homework assignments.

4.2. Data collection and analysis

In order to measure the effectiveness of the AR application, a quasi-experimental design was adopted. The two recitation sessions, taught by the same teaching assistant, were used as the experimental and control groups. Data sources included a pre-test, a post-test, and a survey. Students were given a quiz, as the pre-test, during the lecture to capture their baseline knowledge. In this quiz, students were asked to sketch a deflection diagram of a frame given its bending moment diagram and other parameters. Responses were graded out of 10 points based on the accuracy of the deflection directions and curvatures. Next, students were divided into the experimental and control groups based on their enrolled recitation sections. Even though attendance in these recitations was not required, it was strongly recommended. In the control group, the course teaching assistant solved a deflection example problem using a traditional board and chalk approach. The experimental group, on the other hand, observed the deflection behavior of the frame by manipulating different variables in the AR application. Both groups then took another quiz, the post-test. The post-test quiz was similar to the pre-test quiz so that the learning gain could be accurately measured; however, it was slightly changed (i.e. the direction and the magnitude of the force) in order to avoid learning by mimicry. Out of the entire student population enrolled in the course, only students who took both the pre-test and post-test quizzes were included in this study. Table 1 displays detailed information about the participants.

Table 1
Participant information.

	Junior	Senior	Graduate
Control group (N = 19)	12	7	–
Experimental group (N = 22)	7	16	1

The experimental group also completed a survey investigating students' attitudes toward learning structural analysis in an AR environment. The survey was adapted from Wojciechowski and Cellary [53] and was based on a Technology Acceptance Model [82]. In particular, the survey measured interface style, perceived usefulness, perceived enjoyment, perceived ease of use, attitude toward using, and intention to use. It also included two open-ended questions asking students to reflect on the positive and negative aspects of learning using an AR application. Descriptive statistics was used to analyze the quantitative data. A one-way ANOVA was employed to determine any significant difference between the performance of experimental and control groups as well as pre-test and post-test results. Survey findings were analyzed using means and standard deviations. Qualitative data, on the other hand, were manually coded to identify recurring themes and categories.

4.3. Findings of the pilot study

The next two subsections introduce the quantitative and qualitative results. The results of the experiment are discussed in Section 4.3.3.

4.3.1. Effectiveness of AR in teaching structural analysis

The effectiveness of the AR application was measured through the test score (10 point max.) difference obtained from a pre-test and a post-test. The statistical data obtained is presented in Table 2.

As shown in Table 2, the mean value of the post-test for the experimental group is higher than the mean value for the control group. However, it should be noted that the pre-test mean value for the experimental group was 6.37. On the other hand, the learning rate of the control group is higher, since the mean value for pre-test was 5.59 while this value for the post-test was reported as 6.66. In order to understand whether there is any statistical relevance and significance, a t-test with $t(18) = 0.64$, $p = .05$ and a variance ratio of 0.84 was first applied, which verified that the score distribution was homoscedastic. Next, a one-way ANOVA test (a standard statistical analysis tool) was conducted which compared the mean scores and variances of experimental and control groups. The results did not present any statistically significant differences between the two groups. The one-way ANOVA test results are presented in Table 3. Further details regarding one-way

Table 2
Statistical data from the pre- and post-test scores of the experimental and control groups.

Group	Pre-test		Post-test	
	Mean	SD	Mean	SD
Experimental	6.37	2.56	6.84	1.96
Control	5.59	2.65	6.66	1.89

Table 3
Results of one-way ANOVA test.

Source	Degrees of freedom (DF)	Sum of squares (SS)	Mean square	F ratio	Prob > F
Condition	1	3.60324	3.60324	0.4110	0.5252
Error	39	341.88457	8.76627		
C. total	40	345.48780			

ANOVA analysis can be found in Winer et al. [83].

The results show that the AR application yields a similar outcome in comparison to traditional textbook learning. This would indicate that using the AR interface design to present interactive structural analysis content is at a minimum, as feasible for learning and practicing structural analysis problems as the traditional classroom education. However, the results are not statistically significant, i.e. using AR did not holistically improve student learning outcomes compared to traditional textbook learning.

4.3.2. Student perspectives on the use of AR for teaching structural analysis

The survey results indicated the potential of the AR tool to improve students' experience in learning structural analysis concepts. This finding also confirms similar observations made in previous studies [76]. As seen in Table 4, on a 5-point Likert scale, students in the experimental group positively rated the interface style, usefulness, ease of use, enjoyment, attitude, and intention to use. The only items that were rated lower than 4 (agree) were items 14 and 17.

4.3.3. Discussion

Although the quantitative results are not statistically significant, they have allowed us to identify obstacles when using AR in combination with the mostly positive qualitative feedback to the open-ended questions. In previous research, AR-based pedagogical techniques have been investigated for a variety of contexts, and it was concluded that AR can easily be adopted for teaching STEM courses. However, the unique challenges associated with teaching structural analysis hinder the immediate adoption of existing AR interaction and visualization concepts for this purpose. Observations made during this study suggest that incorporating all AR design concepts and their respective features into one AR application design might be misleading.

First, we have assumed that using morphed, context-related 3D models to show the content is the right solution. In particular, the visualization features were considered to be highly beneficial for learning. Students seemed to have enjoyed the representation of the structure in a way that was easy to visualize as opposed to the 2D images of the textbook. For example, one student cited the visual aspect of the tool as a contributing factor as s/he pointed, "*for a visual learner like myself, this allows you to see how the individual parts come together to affect the entire structure*". Another student commented that s/he liked "*the fact that you could see reactions taking place and how it affected the overall system*". These quotes confirm previous findings that AR enables users to visualize an overall structure and understand how different components influence each other [32].

Furthermore, providing instant feedback to interactive changes in an open application might have led to unsatisfactory students' performance in properly solving the problem. It was particularly observed that some students merely played with the application features and the tablet instead of working on the problem. This indicates that the visualization features may have overwhelmed the students since no further guidance was provided. Our quantitative results partially underpin this theory: the survey item 14 "Learning through the AR system was boring", received a low median value, with a high standard deviation. The survey item 2, "Using an AR application on an iPad is a good idea", has also an unexpected high standard deviation. Responses to both of these questions indicate that some students did not know how to navigate through the problem using the AR application. The responses to survey items 11 and 17 also support this conclusion. Although we have no significant evidence, all results indicate that the application design caters well to half of the class only, and does not address the needs of the other half. Thus, we expect that an application allowing students freely navigate while providing more guidance should address the needs of all students in a class.

The number of items a student had to deal with at a given time was another issue related to the interaction aspect of the AR tool. Students had to point the tablet's camera toward the marker and maintain this position while interacting with the application and reviewing the results. Such application design is not well suited for all students, which was supported by students' answers to the survey questions. One student stated that "*I had to hold [the device] in the air while sliding it, which becomes tiresome after an extended period of time*". A solution to this might be to allow students to be able to freeze the AR image and interact with a still image instead.

Students also pointed out some limitations of the tool, which will help the authors improve the AR application design in the future. Some limitations were due to the nature of the pilot study conducted in this research. Having only one example problem was apparently a limitation as identified by several students. For example, one student mentioned that "*there was only so much you could do. After you achieve it, it was a bit boring. If we had more structures to visualize, it would have been more interesting.*

Despite the implementation challenges encountered during the pilot study and described above, several positive comments were also received. For example, one student reported, "*I liked how you could increase the forces to see how the structural numbers were affected*". Students also seemed to enjoy being able to change the loading as one student stated, "*The ability to change the loading by simply sliding your finger was nice. The [tablet's] ability to show the structure and deformation was better than expected*".

In summary, the results of the pilot study indicated that AR has good potential to enhance students' learning of structural analysis concepts.

Table 4
Student attitudes toward using AR for learning structural analysis (N = 26).

Survey item	M	SD
Interface style (IS)		
1. Navigating the AR application is easy	4.54	0.71
2. Using an AR application on an iPad is a good idea	4.35	1.12
3. I could easily control the course of the structural deflection using the AR application	4.42	0.76
Perceived usefulness (PU)		
4. The use of AR improves learning in the classroom	4.04	0.92
5. Using the AR application would facilitate understanding of certain concepts	4.54	0.58
6. I believe the AR system is helpful when learning	4.08	0.85
Perceived ease of use (PEU)		
7. I think the AR system is easy to use	4.31	0.68
8. Learning to use the system is not a problem	4.35	0.80
9. Operation with the AR system is clear and understandable	4.23	0.99
Perceived enjoyment (PE)		
10. I think the AR system allows learning by playing	4.46	0.76
11. I enjoyed using the AR system	4.08	1.16
12. Learning with an AR system is entertaining	4.19	0.94
Attitude Toward Using (ATU)		
13. The use of an AR system make learning more interesting	4.32	0.75
14. Learning through the AR system was boring (reversed item)	3.80	1.23
15. I believe that using an AR system in the classroom is a good idea	4.23	0.90
Intention to use (ITU)		
16. I would like to use the AR system in the future if I had the opportunity	4.27	0.83
17. Using an AR system would allow me to solve Structural Analysis problems on my own	3.92	1.02
18. I would like to use the AR system to learn Structural Analysis and other engineering subjects.		

In particular, the visualization and interactive features of AR provide advantages not only over traditional teaching approaches and instruction delivery methods, but also compared to other multimedia materials. However, the study also indicates that simultaneously adopting and implementing several AR concepts into a single interface, as well as asking students to point the tablet computer to a marker while maintaining its position and interacting with the 3D model, all at the same time they are evaluating the application feedback may not be appropriate for all students. Thus, we believe that the unexpected low quantitative result is due to the overwhelming interface design, which needs to be addressed in future research.

5. Conclusions and future work

The work presented in this paper reported on the latest findings of a project aimed at transforming current methods of teaching structural analysis using advanced interactive 3D visualization techniques. It was highlighted that despite the fact that structural analysis is a critical part of the curriculum and is taught widely in almost all civil engineering programs, and in most architectural and construction engineering programs, the majority of students do not appear to have a sound understanding of fundamental concepts such as load effects, and load paths; and in general, they lack the ability to visualize the deformed shape of simple structures, a necessary skill to conceptualize structural behavior beyond theory. In this paper, a new pedagogy using mobile AR technology was introduced for structural analysis instruction. In particular, a marker-based AR application was designed for iOS-based tablet computers. This application used fiducial template markers and blend shape morphing to register and render virtual contents over the views of the real world as observed by users (i.e. students). The focus of this study was on the interface design incorporating three AR features: context-related 3D models to convey the content, instant feedback, and collaboration.

In order to measure the effectiveness of the AR application in teaching structural analysis concepts to students, a quasi-experimental design was adopted which consisted of a pre-test, a post-test, and an attitude survey. While the quantitative analysis of results did not yield a statistically meaningful significance, it suggests three contributions: first, 3D models in an AR application can be used to convey structural analysis content despite the perspective camera view, distorted angles, and the changing viewpoints. Second, an interactive application with instant feedback in an open application setting does not provide the necessary guidance to address the needs of all students. Third, the responses indicate that students consider AR as a helpful mean to learn structural analysis. Thus, it can be concluded that AR has potential to contribute to students' learning because of its interactiveness and 3D visualization features.

The pilot implementation indicated that the employed AR interface concepts based on the state-of-the-art design does not yield the expected outcome. In future work, the interaction interface along with instant feedback features of the application will be redesigned by splitting all interactions in an AR navigation mode (moving the tablet and obtaining a video) and an AR interaction mode (interacting with the model). Furthermore, step-by-step instructions on how to use the AR application will be provided to students as guidance. Additionally, various examples covering structural analysis will be developed and incorporated into the learning process. These new examples will include a feedback system integrated into the AR application. It is through this feedback that students will reflect on how different load factors influence the behavior and functioning of structural elements. More importantly, the developed AR learning modules will be better integrated into the curriculum, and students will be guided systematically throughout their experimentation with different structural elements and more complex structural systems.

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