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Mobile augmented reality for teaching structural analysis

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ABSTRACT

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

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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

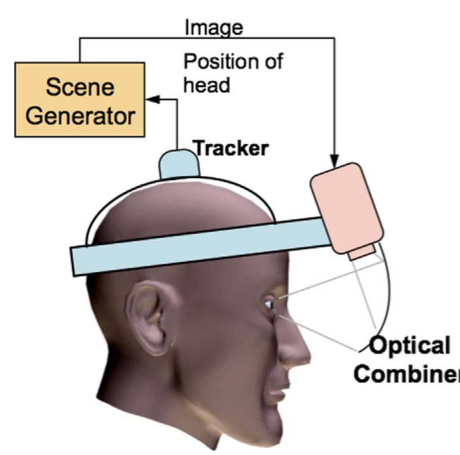

Fig. 1. Work principle of an optical-see-through head mounted display.