Using Advanced Visualization Tools to Improve Construction Education

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ABSTRACT

With recent advancements in software applications and computer display technology, it is now possible to place construction students within a large-scale, immersive projection display that allows them to experience and experiment with a 3D, full-scale virtual model of a construction project. This advanced visual communication can significantly improve the ability of students to comprehend, learn, and gain experience with reviewing designs for constructability and planning the construction of complex building and infrastructure projects.

Results from several experiments that start to illustrate the potential benefits of using virtual reality and immersive projection displays for educating construction engineering and management students are presented. The experiments illustrate the students can develop a more in-depth understanding of the construction process and construction planning by using advanced visualization tools. Key initiatives are defined to provide a roadmap for future efforts toward implementing virtual reality into education.

KEYWORDS

Virtual Reality, Construction Education, Immersive Projection Display, 4D CAD

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INTRODUCTION

Skilled design and construction professionals gain vast experience through their careers by observing and experimenting with the building construction process. It is difficult to provide this opportunity to students in an educational setting. However, one method used in construction education to build this experience is to take students on project site visits. While site visits are a critical component of any design and construction engineering curriculum, the educational quality of a site visit is highly dependent on the activities that are occurring on the day of the visit. A site visit allows students to see one set of activities on a particular type of project (e.g., high rise building), but does not allow students to see how the activities fit together in the dynamic nature of the construction process. Also, students are not actively planning the site logistics and construction sequence, but instead they are passively observing the planning decisions made by others. Therefore, they are able to learn from observation, but not from experimenting and active participation. Advancements in visualization tools provide the opportunity to improve engineering education by allowing students to experience and experiment with virtual design and construction projects in large-scale immersive virtual reality displays.

Four dimensional CAD models (a 3D building design with time as the 4th dimension) and immersive visualization technology, enable students to be actively placed within a building construction site and experiment with decisions that will impact the outcome of the virtual project. This will allow students to gain experience in construction method selection, activity sequencing, site planning, site logistics, temporary facilities, project safety, and project security. Through problem-based project learning modules, students can experiment with different ‘what-if’ scenarios and actively discover unique solutions to construction planning challenges. This active learning in a rich visual environment will greatly improve the current tools and techniques used to educate civil and architectural engineering students.

This paper reports three experiments where the ability of advanced visualization tools was tested for improving student understanding of construction. The results show the promise of these tools at improving student depth of understanding about the proposed construction plans. Moreover, they provide a foundation to understand the future opportunities and direction of advanced visualization tools in the education of construction students.

EXPERIMENTATION WITH 4D CAD FOR CONSTRUCTION EDUCATION

To improve the education of construction engineering and management students within the Department of Architectural Engineering at The Pennsylvania State University, 4D CAD modelling techniques are introduced to students. As this technology was introduced, two experiments were performed to measure the added value for students to use 4D CAD tools when reviewing construction plans. The first experiment was developed to understand the increased perception and understanding that students can gain by performing the 4D modelling process. The second experiment measured the value for students to use 4D models for evaluating and
analyzing complex construction operations. A brief description of each experiment along with the results is provided in the following sections.

**Measuring Increased Perception with 4D CAD Model Development – Experiment 1**

An experiment was designed to assess the ability of students to understand typical planning documents that are used in undergraduate construction education and measure the added value of graphically displaying these plans with a 4D CAD model. The experiment was performed with 25 students in an advanced project management course for 5th year undergraduate Architectural Engineering students in the construction engineering and management program. The objective of the experiment was to determine if students can more accurately interpret and identify potential schedule errors better through a review of a CPM schedule or through the analysis of a 4D CAD model of a building project. Students were taught how to use Bentley Schedule Simulator™ to develop 4D CAD models. Then, students were given a schematic design for a simple office building project (Figure 1) and a 15 activity CPM schedule for the office project. Students were then asked to perform a review and identify any potential conflicts contained within the construction schedule for the building project from the paper documents provided to them. After completing their analysis of the CPM schedule, students developed a 4D CAD model using the Schedule Simulator software. Once the model was complete, students performed a review of the model and answered the same questionnaire regarding the identification of potential schedule conflicts.

Prior to the development of a 4D model, 52% of the students identified a concrete / steel crew conflict intentionally placed within the schedule and only 28% identified a window sequencing conflict from the CPM schedule. After developing and reviewing the 4D model, 84% of students identified the concrete / steel crew conflict and 92% identified the window conflict (Messner et al. 2003).

This experiment illustrates the difficulties that students have in fully understanding a construction plan from reviewing a CPM schedule. The use of advanced graphical communication techniques, like 4D CAD models, greatly improved their understanding of the sequencing issues and made it easier to discuss in class the importance of critical sequencing rules related to concrete and steel construction. A study by Songer et al. (2001) illustrated similar results.

**Measuring Increased Planning Perception with 4D CAD – Experiment 2**

A second experiment was performed to determine if 4D CAD could be a practical educational tool for teaching students the concept of flow as it relates to construction work sequencing. The experiment was performed in a graduate level production planning course with nine students. The students were asked to review the construction sequence for the construction of the Space Hangar of the National Air &
Space Museum project in Dulles, Virginia (see Figure 2). Students were provided with a 150 activity Critical Path Method (CPM) schedule and 2D drawings for the project. Several errors were intentionally placed in the schedule, including space conflicts, inappropriate flow (see Figure 3), and disruption of flow (a pause in trade sequencing).

![Figure 2: The National Air &Space Museum portrait and drawing (the Space Hangar is shown in the photograph at the rear of the Main Hangar, erected but unroofed).](image)

The experiment involved two steps: 1) examining the flow of construction using 2D drawings and the CPM schedule; and 2) inspecting the construction process using the 4D CAD model. The participants were requested to answer the following questions after reviewing the CPM schedule and 2D drawings:

- Think about which contractors would do which part of the project. Connect the contractor to the work (the lists of the work and contractor are given)
- Do you see any improper construction flow? Identify these. What are the characteristics that make them poor flow?

Then the participants reviewed the construction process with the 4D model of the project. The participants were asked to run the model, review the model, and evaluate...
the construction work flow. They were asked to answer the same set of questions as in the first step.

The results of both phases of the experiment were compared and used to determine if the visualization technology would improve the participants’ ability to evaluate the important flow concepts in the construction process. Eight students identified the space conflict in the schedule but identified no other flaws. When viewing the project using the 4D CAD model, all students were able to identify the space conflict. In addition, seven students identified the direction error and three identified the flow disruption when they viewed the 4D CAD model. This shows that students can gain a more detailed understanding of the construction process and potential conflicts by visualizing the construction process in a 4D model (Tan et al. 2003).

**IMMERSIVE VIRTUAL REALITY**

Recent advancements in computer display technology have greatly improved the graphical interface between computers and humans. Through the use of virtual reality, students can now gain a very realistic view of buildings, infrastructure and other graphical models. Howard Rheingold (1991) defined virtual reality as an experience in which a person is “surrounded by a three dimensional computer-generated representation, and is able to move around in the virtual world and see it from different angles, to reach into it, grab it, and reshape it.”

Virtual reality (VR) technology has been used in diverse fields including 3D graphics, video games development, 3D scientific visualization, architectural design, automobile design, and medical research and education. VR in engineering design and construction disciplines is being used to develop and visualize project designs (Messner et al. 2002; Schnabel and Kvan 2002; Shibano et al. 2001); visualize construction plans and schedules (Haymaker and Fischer 2001; Whisker et al. 2003); design and analyze construction equipment (Lipman and Reed 2000; Opdenbosch and Hastak 1994); and communicate and train the project team (Haymaker and Fischer 2001).

Virtual reality can be classified into two broad areas: 1) Desktop VR, and 2) Immersive VR (Bouchlaghern et al. 1996). In desktop VR, the viewer uses a desktop monitor to interact with a virtual model. In immersive VR, a large format or head mounted display is used to immerse the viewer within the virtual environment. There are currently more than 14 different display type categories summarized by Kasik et al. (2002) for immersive VR viewing.

The use of immersive virtual reality display technology can help revolutionize the educational techniques used in engineering education. Virtual environments provide an extremely rich learning atmosphere where students gain a ‘sense of presence’ within the virtual space. This engages students to learn from the virtual experiences that they have within the immersive environment. Another significant benefit of this visualization technology over desktop graphical displays is that students can enter a space at full scale (1:1) which adds more realism to their virtual experience. Research has shown that students learn best from their own experiences and discoveries (Kalisperis et al. 2002a; Kalisperis et al. 2002b; Li and Liu 2003). A virtual environment can greatly enhance this learning experience.
The first large-scale immersive projection display was CAVE™ (CAVE Automatic Virtual Environment) (Cruz-Neira 1993). CAVE™ was developed in 1991 to allow computational scientists to interactively present their research in a one-to-many format on high-end workstations. CAVE™ is an open, three-wall (each 10’×10’) theater built from rear-projection screens and a down-projection screen for the floor. These projectors throw full-color active stereo images. The users wear liquid crystal display (LCD) stereo shutter glasses which separate the alternate fields for each eye to provide a 3-dimensional visual effect. A user’s head and hand can be tracked with electromagnetic sensors to provide interaction with the display system.

Experimentation with Virtual Mock-up for Construction Education – Experiment 3

The Applied Research Laboratory at Penn State University has an immersive projection display system similar to the CAVE™ in the Synthetic Environment Applications Laboratory (SEA Lab) (Shaw 2002). The SEA Lab’s equipment includes a display system that permits the generation of a 360 degree, 10’ x 10’ x 9’ immersive environment where users can collaboratively interact with simulations and data in real-time (see Figure 4). The system uses four back-projection display screens and a top projected floor display; stereoscopic and synchronized image rendering; specialized audio; and magnetically tracked 3D input devices to create a virtual environment. 3D models displayed in the system appear to be continuous from one wall to the next and the effects of the room corners disappear.

A case study experiment was performed within the IPD to assess the potential use of the facility for construction schedule development by students and to evaluate the added value of the immersive display system. For this experiment, two groups of two graduate students were placed within a model of a complex room within a new nuclear power plant design (the Westinghouse AP1000 nuclear power plant).

Each team was able to apply logical sequencing rules for the construction of the different components in the room, however, each team developed a different strategy for completing the room and ultimately developed a different sequence of construction activities. For example, one team developed a sequence based on placing the larger modules into the room first, and then connecting the modules with spool pieces. The other team developed a sequence focusing on the installation of elements and modules...
at low elevations in the room and working toward the ceiling. They also focused on a construction flow from one end of the room to the other end.

The student feedback via surveys and interviews clearly illustrated that they gained valuable scheduling experience in power plant and modularized construction from their ‘virtual experience’ within the immersed environment. They rated the development of the schedule within the environment a nine out of 10 in ease of use. One of the students who has project engineering experience noted on their survey form that the IPD was extremely helpful in gaining a clear understanding of the project in much less time than blueprints or even 3D models (Messner et al. 2003).

The results of this experiment suggest that students can quickly understand complex virtual building models and gain experience from planning the construction of these virtual projects. Students are engaged by working in the immersive environment where they can learn and, due to the rich visual environment, develop a detailed understanding of complex design and construction decision processes. It is also possible to provide a critique of the different construction sequencing and planning decisions made in the virtual environment and much can be learned by students from seeing and experiencing other solutions to the same problem.

THE FUTURE OF VISUALIZATION IN CONSTRUCTION EDUCATION

To achieve the full benefits of using immersive virtual reality in design and construction education, future research and education efforts must focus on four main areas: 1) low cost display system development, 2) construction planning applications in VR, 3) educational case study content for the systems, and 4) pedagogical research to assess the benefits of VR for construction education. A discussion of each follows.

Low Cost Display Systems

To achieve large scale implementation of the use of VR, and particularly immersive VR, in construction education, it is necessary to identify technologies that allow for the development of low cost immersive projection display (IPD) systems. Large scale, high end active stereo display systems like CAVE™ by Fakespace Systems or MD SSVR™ by Mechdyne Corporation provide excellent detail for viewing large models in an immersive environment. But, these systems are currently too expensive for universities to purchase for student education since many visualization laboratories spend more than US $1 million for the immersive display and related required improvements. To date, these systems have predominantly focused on highly specialized research performed by a limited number of researchers.

Several universities and commercial initiatives exist to reduce the cost of immersive display systems. At Penn State, a low cost immersive display systems has been developed to allow students to visualize 3D models on a low cost, three screen passive stereo display system (Kalisiperis et al. 2002a). This low cost immersive project display is used in undergraduate architectural studio courses. It is also possible to purchase scaleable immersive systems where the number of screens for the system are selected. Vendors are starting to offer lower cost, passive stereo, immersive display systems which can be used for visualization in education (e.g., CADWall™ by Barco...
Simulation Products). The development of new and lower cost display systems will continue to make higher resolution, faster, and lower cost immersive display systems available to educators in the near future.

**Construction Planning Application for Virtual Reality**

Many software applications do not support stereoscopic viewing. Recently, some CAD applications are adding functionality so that users can work within an immersive display system. While this functionality is very valuable, many applications still do not support multiple wall projection display systems or allow for magnetically tracked input devices. Due to these restrictions, the use of commercial CAD applications within IPDs is very limited.

There is a need to develop new applications and tools that can be used within IPDs for the authoring of educational modules. The applications should include the ability to view a 3D CAD model along with the ability to generate and view construction schedules through dynamic 4D models. In addition, there should be an underlying product database which allows the users to view building product attributes, e.g., material type, cost, production, schedule, etc. Other functions, including the ability to isolate various systems (e.g., the plumbing or electrical system) and the ability to follow scripted viewing paths is important for the development of educational models.

**VR Educational Modules**

The best applications and display systems will not be useful without well developed educational case study content. Two types of content would provide value to the construction educator: highly visual presentation material for class lectures and discussions; and experimental learning models. The first would be presentation material that would allow for interactive presentations. An example of this type of learning material would be project models showing the various systems and the construction methods and schedules used for constructing the buildings.

Constructability, sequencing, method selection, safety, system design, and other critical issues could be represented in these models.

The more challenging educational content is to develop interactive experimental learning models for students. These modules would allow students to enter a virtual building model; perform design and constructability reviews; develop construction sequences; select temporary equipment; identify space requirements; and perform safety reviews. Modules could be developed to allow students to experiment with the design and construction process and easily test ‘what-if’ scenarios. The students could then ideally present their solutions for an educational module to the class in a studio style presentation.

**Pedagogical Research to Assess VR Benefits**

It is important that research on the pedagogical value of using active learning exercises in an immersed VR environment be performed. The objective of this research should be to perform a detailed assessment of the impact of the learning objectives of students in the modules within the construction engineering and management programs. It is important that students learn how to use advanced
technology for performing construction planning, but it is more important that students learn the core knowledge and skills that they will need to be productive and successful in the construction industry. The educational modules will allow them to do this.

**CONCLUSIONS**

Construction engineering and management require very sophisticated visual skills in its practitioners. The education techniques to teach construction must continue to pull from the best visualization techniques available. The exploratory case study experiments presented in this paper illustrate the potential value of using highly visual modelling techniques through the use of 4D CAD and immersive display technology to enhance construction education.

The academic community and commercial technology developers must continue to advance the level of maturity in four areas to make the extensive use of immersive virtual reality an integral part of construction engineering education. These areas are the development of low cost display systems, virtual construction planning applications, educational case study content for the systems, and pedagogical research to assess the higher level educational benefits of advanced VR for construction education.

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