Using Virtual Reality to Improve Construction Engineering Education

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Abstract

This paper presents ongoing research to improve construction education through the use of virtual reality and 4D CAD modeling (3D design plus time) of construction processes and projects. We have implemented 4D CAD modeling into our undergraduate Architectural Engineering program. We are also experimenting with the use of immersive virtual reality and have developed a tool that allows construction engineering students to interactively generate a construction sequence for a project in an immersive environment. The results of these educational initiatives were assessed through two experiments. The first experiment assessed the educational value of having students develop 4D CAD models for a building project. The second experiment was a preliminary study to determine the educational value of immersing students in a virtual construction project and allowing them to develop a construction plan for the facility.

The results of these experiments suggest that students can understand construction projects and plans much better when advanced visualization tools are used. The conclusions from the immersive virtual reality experiment suggest that students can very quickly gain experience by developing and critiquing construction schedules in a full-scale virtual environment. The students were also very engaged by this type of interactive learning experience. We envision important applications of this type of learning environment to improve construction education through the use of different case study projects. By using virtual reality, we can supplement actual construction site visits with virtual, interactive site experiences. These experiences will allow students to experiment with different construction sequences, temporary facility locations, trade coordination, safety issue identification, and design improvements for constructability.

1. Introduction

Students in Civil and Architectural Engineering programs currently learn to analyze the designs for building and infrastructure projects and plan their construction by reviewing 2D project design drawings and by developing construction cost estimates and schedules. While some designs are generated in 3-dimensional Computer Aided Design (3D CAD) format, few advanced visualization techniques are used in higher education. For example, educators tend to use 2D drawings and Critical Path Method (CPM) schedules to discuss project planning. These visualization tools limit the students' ability to comprehend the impact of design and planning decisions on projects. With recent advancements in computer display technology, it is now possible to place our 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. In addition, the use of advanced visualization techniques will engage students in an active learning process.

To date, 4D Computer Aided Design (CAD) modeling (3D CAD with schedule time as the 4th dimension) on desktop computer monitors has been implemented in the undergraduate curriculum in Architectural Engineering at Penn State. Students develop a 4D CAD model for a simple building project within an advanced project management course (AE 473). The objective for integrating the 4D CAD tool into the program is to have students learn the benefits of using advanced visualization tools for developing and communicating construction plans.

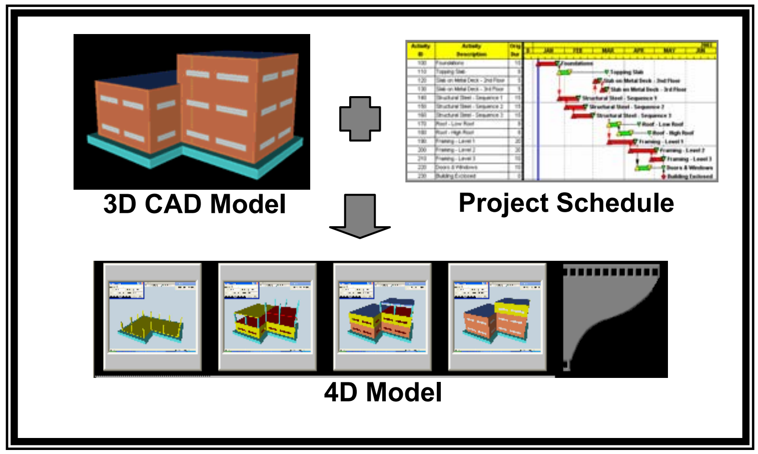

Figure 1: *4D CAD Model Development*

2. Virtual Reality Background

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[1] 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 3-D graphics, video games development, 3-D 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[2-4]; visualize construction plans and schedules[5, 6]; design and analyze construction equipment[7, 8]; and communicate and train the project team[5].

Virtual reality can be classified into two broad areas: 1) Desktop VR, and 2) Immersive VR[9]. 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[10] 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[11-13]. A virtual environment can greatly enhance this learning experience.

The first large-scale immersive projection display was CAVE™ (CAVE Automatic Virtual Environment)[14]. 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.

3. Virtual Reality Display Facility at Penn State

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)[15]. 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 2). The system uses four back-projection display screens; 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.

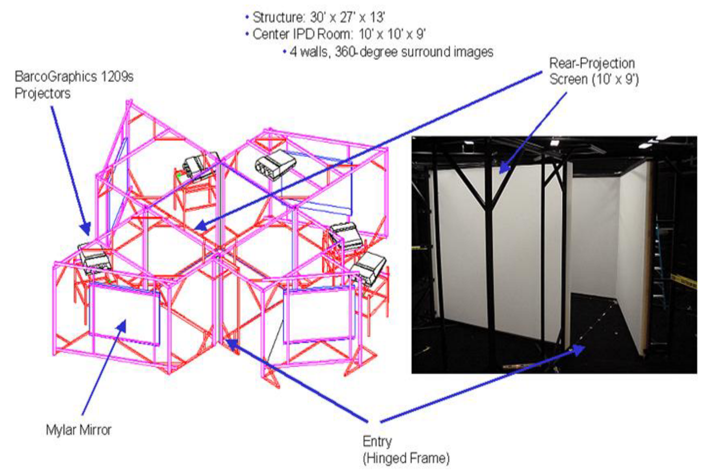

Figure 2: *SEA Lab Immersive Projection Display at Penn State Applied Research Lab*

CAVE™ and CAVE-like facilities have been successfully used in research for such diverse applications as the visualization of complex fluid flow patterns around propellers, to assist with urban planning, to visualize the internal operations of complex machinery, and to aid in the design of complex tests. At Penn State, we have been experimenting with the application of VR in design and construction of buildings and infrastructure in the SEA Lab[4].

4. Measuring the Educational Value of 4D CAD and Immersive Virtual Reality

The following sections present the results of two experiments performed to assess the educational impact of the use of 4D CAD and advanced visualization tools on construction engineering education.

4.1. Measuring the Value of Using 4D CAD for Construction Engineering Education

The first experiment was designed to assess the ability for students to understand typical planning documents that are used in undergraduate construction engineering 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 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^{TM} to develop 4D CAD models. Then, students were given a schematic design for a simple office building project (Figure 3) and a 15 activity CPM schedule for the office project (Figure 4) developed in the Primavera P3 scheduling application. 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.

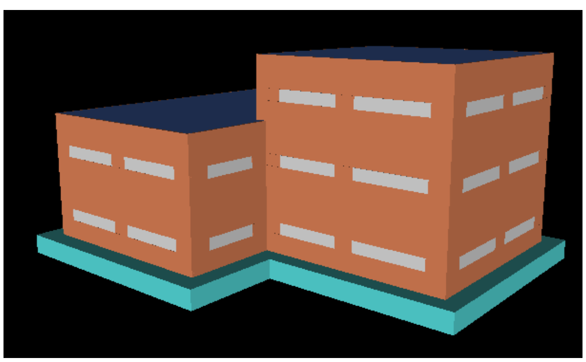

Figure 3: Perspective of Office Building

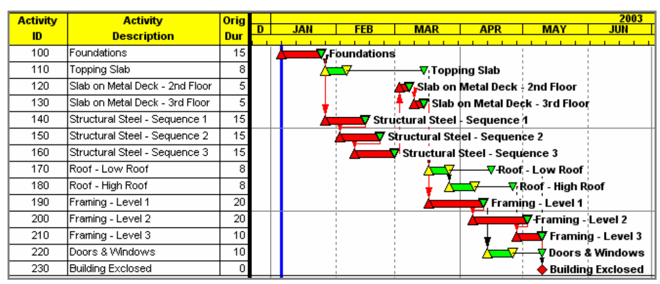

Figure 4: CPM Schedule for the Office Building Project

Two sequence conflicts were intentionally placed within the schedule to determine if the students would identify these errors from a review of the CPM schedule. The schedule contained a crew / safety conflict between the concrete slab crew and the steel column construction crew on the first floor. The schedule also contained a physical construction sequence error since the third floor windows were being installed prior to the construction of the exterior wall on the third floor. Table 1 shows the results of the student experiment. Prior to the development of a 4D model, 52% of the students identified the concrete / steel crew conflict and only 28% identified the window 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. A study by Songer et. al.[16] illustrated similar results.

Table 1: *Results of 4D CAD Student Experiment*

	From CPM Schedule		After Completing 4D Model	
	110-160 (Steel/Slab)	**220 (Wall/Windows)**	**110-160 (Steel/Slab)**	**220 (Wall/Windows)**
# of Student that Identified Conflict	13	7	21	23
% of Student that Identified Conflict	**52%**	**28%**	**84%**	**92%**

The results of this experiment clearly show that students can understand a 4D CAD model better than they understand the CPM schedule and construction drawings provided to them. 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.

4.2. Measuring the Value of Immersive Virtual Reality to Improve Construction Education

A second experiment was performed to determine the value of using advanced visualization techniques to improve the ability of students to analyze and generate a 4D model. To perform this experiment, a 3D model for a nuclear power plant project, the Westinghouse AP1000 nuclear plant, was placed into the CAVE-like immersive projection display. The experiment focused on the construction of one complex room (Room 12306) within the auxiliary building of the plant (see Figure 5). Room 12306 contains a large construction module (KB 36), a smaller off-platform module, several large pipe assemblies, two air handling units, a fire protection valve assembly, and approximately 20 pipe spool pieces. The AP 1000 is designed to be constructed using prefabricated modules which are built off-site and shipped to the project location. The modules are then hoisted into place and connections are made in the field. This makes that sequence of construction of the modules and large assemblies a critical planning activity.

To perform the experiment, the IPD was programmed to allow students to interactively develop a sequence of construction for Room 12306 within the immersive environment by selecting and sequencing the graphical objects. Two teams, each consisting of two Architectural Engineering graduate students, were placed into the IPD (see Figure 6). After a scripted introduction to the room and its components, the students developed a sequence of construction for the different elements within the room.

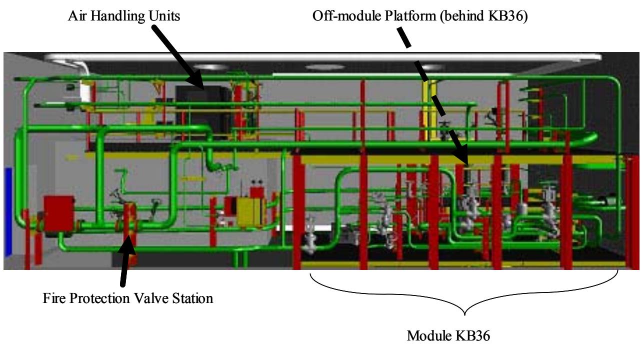

Figure 5: *Room 12306 (section view)*

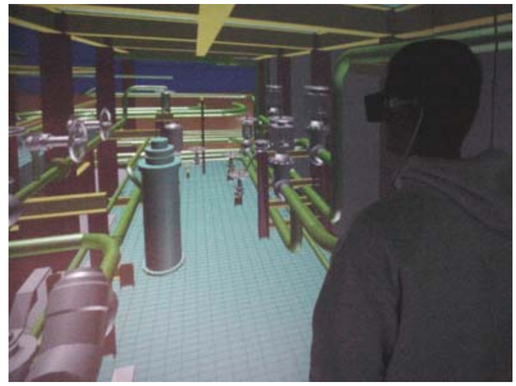

Figure 6: *Student in SEA Lab IPD*

Each team was able to apply logical sequencing rules for the construction of the different components in Room 12306, 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.

Standing in the room before and during the construction simulation encouraged discussion of the actual methods of construction that would be used. The students discussed the use of spreader beams for hoisting large pipe assemblies. They also mentioned module size limitations and accessibility issues for some of the field weld locations. The enhanced spatial perception offered by the virtual reality system allowed the students consider workspace interferences between trades while they planned a number of parallel activities. Using the immersive schedule development software, the students were able to develop a reasonable installation sequence in approximately one hour with no prior introduction to the space and little experience in nuclear power plant construction.

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 9 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. The students rated their confidence in the schedule that they had developed as an 8 out of 10.

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.

After completing this experiment, two additional groups consisting of two experienced construction professional were placed in the IPD to evaluate construction plans that they developed for the same room within the power plant. The sequences and reasons behind their solutions were more extensive than the student teams, but their solutions confirmed that many of the sequencing strategies used by the students were logical. The industry teams also illustrated the value of using immersive virtual reality for planning actual construction projects.

5. Challenges to the Implementation of Virtual Reality in Construction Education

While there seem to be clear benefits to using virtual reality for construction engineering education, there are several challenges that educator face in implementing the use of this technology. First, large virtual reality facilities (e.g., CAVE and CAVE-like systems) provide very high resolution images with many advanced visualization and magnetic tracking features. This provides a high quality visual display system, but it also costs a large amount of money to construct these display systems (typically over $1 million). The second limitation of the CAVE-like systems is that the facilities typically have a small footprint which limits the number of people who can comfortably fit within the space (typically 4 to 6 people). Therefore, these facilities have traditionally been used for high-end research projects by a limit number of researchers[13]. To overcome these impediments, it is necessary for universities to investigate new, low-cost immersive projection display systems for educational purposes. There are currently low-cost immersive display facilities in use. An example is the Immersive Environments Lab (IEL) which is used for architectural studio education[13]. More research into the construction of these low-cost facilities is needed.

There is also a need to continue the development of tools that can be easily used by students to generate dynamic construction models in immersive displays. There is currently limited software that will allow stereoscopic viewing of 3D and 4D CAD models. Frequently, students must export or convert these models from one format to another. There is a need to make software easier to use within virtual reality environments.

As the software and displays become more robust, educators must create (or transform from other graphical media) case study projects that will help students meet the learning objective of our undergraduate and graduate curricula. Even though students will learn about the application of advanced technology in construction by using these tools, the goal should be to develop case studies or learning modules that help students gain a more detailed understanding of the construction process.

6. Conclusions

Construction engineering is a visual discipline which requires an advanced ability for students and professionals to visualize complex spaces and objects. It is important that we use the most advanced visualization tools to help educate future construction engineers. When better graphical models are presented to students, they will learn important construction planning concepts more quickly and be engaged in their learning experience.

It is clear that our undergraduate students have difficulties in understanding the current graphical techniques that we use to teach students how to plan construction projects. These tools focus on the development of Critical Path Method (CPM) schedules from primarily 2 dimensional drawings. While it is critical for students to learn how to understand these graphical representation methods, their limited visualization ability limits their understanding of topics discussed in classes and presented through course assignments.

The results of the experiments presented in this paper suggest that 4D CAD modeling and the use of immersive virtual reality display systems can improve the education of construction engineering students. There are many challenges that need to be addressed by educators interested in using these tools including the development of lower cost immersive display systems, the development of tools that allow students to create and present construction plans for virtual projects, and the creation of good educational modules. Even though we face many implementation challenges, advanced visualization technologies present an opportunity for educators to provide virtual experience to students in construction engineering education. These technologies will allow students to develop a detailed understanding of planning issues that they currently do not gain due to their limited abilities to visualize building and infrastructure designs.

7. Acknowledgements

We wish to thank Tim Shaw, Eileen Rotthoff and Michael Warren for their work on the development and execution of the virtual reality experiments in the ARL SEA Lab; Jim Winters, Jill Clelland, and Tom Johnson at Westinghouse Electric Corporation for providing the information and support needed to develop the virtual power plant model; and Shawn Bell of Turner Construction Company for assisting with the 4D CAD student experiment.

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