Interactive and Immersive Training
in a Virtual Environment for Construction Students

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Introduction

Construction projects involve a wide range of operations and activities, most of which can lead to accidents if proper care is not taken. The most serious construction accidents involve construction equipment operation, trench and embankment failure, falls from elevated positions, collapse of temporary structures and forms, and the failure of structures under construction. [1] Tragic construction accidents have had catastrophic consequences. The collapse of the Quebec Bridge during construction in 1907, in which 74 men were killed, is considered one of the worst tragedies of the century. In recent years, 51 people were killed during the construction of a cooling tower in West Virginia, and another 113 died when walkway bridges collapsed in Kansas City's Hyatt Regency Hotel.

In 1980, the National Safety Council (NSC) reported that worker's injury rate accounted for nearly 11% of all work injuries and more than 20% of fatalities. [2] In the 1990s, in spite of years of efforts by the industry and government regulatory offices to introduce new safety regulations and safety-oriented construction techniques, these high injury and death rates have not decreased. In fact, in 1990, *The Business Roundtable* reported that the worker's injury rate in this industry was about **54%** higher than the rate of all other industries combined. [3] In addition, the death rate in construction is **71** per 10,000 workers versus an average in all industries of 18 per 10,000. Over 200,000 construction workers suffer disabling injuries each year, and over 2,000 construction workers die as a result of work-related injuries each year. [4]

A survey of 120 structural failures conducted by the Institution of Structural Engineers in the United Kingdom [5,6] reveals that inadequate construction education is one of the important factors leading to the above failures and accidents. To achieve a well constructed project the institution recommends that construction education include the following education enhancement factors: practicality and feel for engineering construction, knowledge of overall structural behavior, creative thinking and problem solving, accuracy of assumptions made in the design, and engineering j udgment. In turn, all these factors allow students to understand the underlying causes of failures. Therefore, it is imperative for civil engineering educators to promote these education enhancement factors to our undergraduate students in the classroom. [7,8]

In reality, many civil engineering undergraduate programs fail to provide students with an arena where they can acquire the construction skills and experience necessary to perform successfully at on-site operations. [9] Most civil engineers need to spend many years in the field in order to assimilate an adequate knowledge about actual construction performance. However, the development of new materials, innovative approaches to construction, and computer-based management systems in the construction industry now require

construction engineers to have a more scientific background and to be qualified in a shorter time. With such rapid technological advances currently characterizing the construction industry, adequate classroom substitutions for field experience are increasingly necessary.

As an example, in an earlier course term project of courses, such as the Construction Methods and Equipment, students assume the role of a construction engineer responsible for a construction project, such as a deep foundation construction for a high-rise building; a cofferdam installation for a bridge foundation; and erection of a concrete or steel building/bridge. Students selecting the erection of a bridge construction project are given the plan drawings and specifications of the project and are encouraged to contact designers, contractors, subcontractors, suppliers, and vendors to obtain information relevant to the task. They begin with site preparation. Then, they perform alternative selection for a safe yet economical type of girders, bracing, and deck. Next the students decide upon the technique and sequence of the construction process, including the selection of appropriate equipment. Subsequently, they determine the step-by-step operation of the erection of the girders and the concreting procedure of the bridge deck. Finally, the students estimate the time and cost required to complete the project. Potential problems and methods of avoiding or mitigating such problems are evaluated. The students submit their report at the end of the quarter. While such an exercise is useful for students, they have to spend a great deal of time on the project and yet, may not fully understand the entire process of completing the construction project.

An efficient response to this need is to perform studies through the use of a simulation laboratory. Researchers are acutely aware of current laboratory educational issues, the extent of the problem, and what others have done. These issues have been addressed through the development of several undergraduate laboratories.[10,11,12] Consequently, this study, called Construction Operations using Virtual Reality (COVR), attempts to solve the educational problem. Virtual reality (VR) models that extend well beyond the instructional capacity of the equipment will be used for simulating construction operations. It is expected that this innovative technique for using laboratory exercises to improve students' understanding of basic engineering principles will establish the education enhancement factors.

VR technique in Engineering Education
Fisher[13] defines a VR technique as an "innovative way that represents first-person or direct experience through the development of multi-sensory media environments in which viewers can interact with the information presented as they would in encountering the original scene." The essential attributes of VR are its simultaneous immersive and interactive capabilities, which cannot be obtained through the use of other techniques. With the application of computer graphics, a head-mounted display (HMD), and a tracking system models developed using virtual reality could become almost real.

An analogy can be made by comparing ourselves viewing the Hyatt Regency collapse scene by television and watching it live. In the latter, we can view the scene from any desired direction, and even participate in assisting the victims. To reach such immersive and interactive capabilities in a computer-generated environment, a certain technique of putting images and objects in front of our eyes and blocking the eyes from the real world (e.g., through the use of an HMD or a binocular omni-orientation monitor) is required so that the total view, no matter which direction we turn (much the same as in viewing a scene from any desired direction) encompasses only the virtual world.

The benefit of VR is its immersion, navigation, and interaction capabilities in a virtual world. The first feature, immersion, allows users to feel as if they are completely in a virtual world. Such an immersion can be

achieved through the use of an HMD. Second, the navigation permits the user to walk through and observe the virtual environment from any view point and angle. By comparison, traditional video presentation limits viewers to the position of a camera and, once videotaping is made, only a single view point is available — viewing other sides is no longer possible. The last feature, interaction, lets the user touch, lift, or move objects in the virtual environment. Consequently, users feel as if they exist in the virtual environment. In its application to construction operations, the most important VR characteristics are among others:

. First-person experience. Users of VR applications can obtain the feeling and experience of being on a real construction site.

. Safety. The virtual environment allows the users to train and be trained in a safe environment without subjecting themselves to real hazardous conditions.

. Economy. A VR model can be used to represent various operations, situations, and conditions since the 3-D object models can be modified relatively easily. The variety of operations represented by the models can be produced in the same laboratory with the same equipment,

• Teamwork. A networked VR system can be used by multiple users working at the same time (e.g., trainer and trainees).

The above characteristics of VR make it an ideal tool for education and training our construction students. VR emphasizes first-person experience, which is an important aspect in education, but which, because of safety considerations, budget limits, and lack of personnel, often cannot be fulfilled. For a construction engineering program, field experience is hard for a school to provide. Video presentation can concisely show the construction of a project, but students are not personally exposed to the operations in a construction site and do not have the opportunity to walk around to observe a desired process. A site visit is a good means for students to experience an actual construction, but safety, budget, and time constraints sometime discouraged instructors to arrange such activities.

On the contrary, VR can provide students with the experience of "walking" through a construction site and "participating" in construction operations. Furthermore, VR has the potential to reshape traditional teaching and instruction methods. For training purposes, by repeating specific operations and immediately responding to unexpected incidents VR provides trainees with a safe and economical method to gain a construction skill.

As in the case of any new technique, research and development (R&D) in VR technology has its barriers. One and foremost was dubbed by Hancock[14] as the "Hollywood syndrome" where "the idea that VR is strictly for images of other worlds where one can get lost, lie idle, and generally play around." Because of this reputation, the real value of VR in R&D is often lost. This is particularly true since earlier VR applications in the US have flourished in the entertainment industry. [15,16,17] As a learning tool, Traub from Center Point Communications, San Jose, California]* noted that "[VR's] potential as an ultimate learning tool is unlikely to be implemented where it is most needed--in addressing the US educational crisis. . ..it is typical that new technologies are first channeled to institutions such as the military, business and entertainment industries that American society deems more important." Examples of VR research for military purposes are, among others, NASA's visualization of computational fluid dynamic data in a virtual wind tunnel[16] and the U. S. Army Corps of Engineer's water flow simulation through a rip rap test channel at Vicksburg, Mississippi. [19] To sum up, in his book, *Virtual Reality,* Rheingold[15] added that "educators were the last people to ask for millions of dollars for R&D."

As a result, Japanese researchers are now leading in the R&D of VR technology. Models and prototypes were developed in numerous domains, ranging from education to industry; they are, to name a few, *Virtual Kitchen* by Matsushita, *Model House Room* by Shimizu, *Virtual Brewery* by Sapporo Beer, and *Virtual Telephone* by NTT.[20] Consequently, in 1992, a consortium of federal agencies (Advanced Research Project Agency, Air Force Office of Scientific Research, National Aeronautics and Space Administration, National Science Foundation, and National Security Agency) requested the National Research Council to establish a Committee on Virtual Reality Research and Development to provide directions in the research and development in the area of VR. In 1995, the Committee identified four domains of VR application: (1) design, manufacturing, and marketing; (2) hazardous operations; (3) training, and (4) medicine and healthcare.[21]

Inevitably, a change of attitude towards R&D in VR technology in the US has occurred. As an example, in the area of mechanical engineering, VR research was recently conducted to add motion, functionality, and intelligence to solid models so they can be evaluated in a synthetic environment.[22] In civil engineering, virtual machines and interactive visualizers have been developed for training heavy equipment operators.[23] In addition, VR models were recently developed for designing the Florida Turnpike.[23] Many other models are currently being developed; they have not yet been published but are announced in the World Wide Web. At the Ohio State University, research in VR has produced, among others models for use in hazardous operations and training[24,25,26].

Model Development for COVR

With the help of experts in the Ohio Department of Transportation (ODOT), a highway overpass located in New Albany, Ohio, was chosen to be implemented for the first case. The bridge, which was designed by a civil engineering firm in Columbus, Ohio, measures 195 feet [60 m] long and 72 feet [22 m] wide and has eight steel girders under the two-span continuous deck. Each of the girders is composed of three pieces by bolting and the concrete deck is cast on site. The construction project began in April of 1995 and was completed in October the same year.

To show the bridge in a virtual reality environment, the 3-D models (in terms of computer files) are constructed. The original drawing files, which were stored in the AutoCAD R12 file format, were obtained through the courtesy of the civil engineering firm. However, these drawings were sketched in 2-D space; hence, they should be imported into a virtual environment such drawings had to be converted to 3-D object models. The 3-D modeling software for this project was AutoCAD and 3D Studio, which functionally complement each other and therefore, were used together. AutoCAD has functions for locating an exact position by typing numbers, snapping special points such as end points, intersect points, and tangent points. Further, it can perform union, subtraction, and intersection of 3-D objects, but does not have the capability to apply texture mapping on objects. On the other hand, 3D Studio, although its use to locate an exact point and to snap a vertex is more difficult than AutoCAD, has a robust material editor, which can be employed to compose colors, textures, and surface properties of materials. Consequently, the procedure for constructing a 3-D object is, first, using AutoCAD to construct the 3-D shape of the object, and then employing 3D Studio to apply color and texture mapping.

After producing the 3-D objects, we can begin to import these objects into a virtual environment. To develop a VR application, it is not necessary to program from scratch. In the computer graphics market, there are some existing 3-D graphics libraries, which have encapsulated rendering processes and scheduling processes of simulation loops. Developers only have to pay attention to where to transform 3-D objects, how to allow users to interact with 3-D objects, and how to simulate the behavior of objects. SenseS's

WorldToolKit (WTK), which is a C language library and is the first one of its kind on the market, was selected as the implementation tool kit. There are two main reasons for choosing WTK: the multi-platform capability and various sensor drivers. Hence, a program developed on one platform using WTK can be easily ported to other platforms. However, the performance may vary with the capability of the computers. It also provides many drivers for various sensors, such as a mouse, 3-D mouse, joystick, six-degrees-of-freedom (6-DOF) sensor, and CyberGlove, so that these devices can be easily operated.

A VR system consists of software and hardware. The software is a program which interpret data from hardware and shows the results in 3-D graphics format, while the hardware includes tracking devices and sensors. The execution of the program is conducted by a simulation manager, which arranges the order to execute activities in a simulation loop. A simulation loop can be divided into five steps: (1) reading sensors, (2) running the universe action function, (3) updating objects, (4) running object tasks, and (5) rendering the universe. The first step, reading sensors, is to check the displacement of sensors between a simulation loop and an earlier loop. The second step is to execute the universe action function, which is used to define some repeated activities having global effect such as reading the keyboard input. Next, the object's position and orientation will be updated according to the reading from sensors. Then, object tasks, each of which processes the activities affecting some related objects, are executed. For example, collision detection is usually implemented in object tasks. Finally, the universe is rendered on the screen through the use of WTK functions.

Simple VR applications which only allow users to walk through a virtual environment are insufficient for education and training purposes. To develop a virtual environment for COVR, dynamic interaction is essential. In a VR program, such an interaction should include the creating 3-D objects, performing physical simulation, and reading sensors. The graphics supercomputer we are using to develop the model is the Onyx RealityEngine2 (Onyx RE2), from Silicon Graphics Inc. The Reality Engine2 of the computer provides adequate performance of texture mapping and speed of operation. Therefore, Onyx RE2 produces realistic VR models. This machine is highly recommended for use in VR research by the National Research Council Committee on Virtual Reality Research and Development.

In developing the model for COVR, we employed two ways to create graphics objects in a virtual environment: static and dynamic. Objects constructed during their development in which their shape will not be changed at run time are called static objects, while dynamic objects are established at run time by the user input or specific conditions. Static objects are usually constructed with 3-D modeling tools and stored in files, and when the program is running, these files are imported to create graphical objects. Dynamic objects have to be constructed by program code because some of the dimensions are variables. For example, when users decide to add a girder into a virtual environment, and the type and length of a girder are input by users, the girder has to be constructed dynamically at run time. Some subroutines have been created for creating standard concrete and steel beams.

Objects appearing in the virtual environment ought to follow the laws of physics in order to appear real. Physical simulation, such as collision and gravity effect, is important for a VR application, because humans are used to these physical phenomena and a virtual world would lose its reality without physical simulation. However, there is a trade-off between frame rate and reality. More realistic images will lower the frame rate, and low frame rate will cause users to feel uncomfortable and experience "cybersickness." Collision detection and gravity effect have been implemented in the project. Collision detection is used to prevent objects from overlapping each other so that all objects should perform collision tests every time they move. Consequently, the collision detection mechanism ought to be planted in object task functions. Usually, a

collision test is performed by detecting whether two bounding boxes of objects intersect each other. If the boxes intersect each other, the two objects are regarded as colliding.

Sensors are used for interacting with a virtual world. The sensors for this project include Polhemus Fastrak, Eyegen3 HMD, and CyberGlove. Polhemus Fastrak is a tracking device with four 6-DOF sensors, each of which can detect the position and orientation of a point. The sensors can be attached on a head or a hand to work with an HMD and a CyberGlove. An HMD basically consists of two small monitors for vision, two earphones for audio, and a 6-DOF sensor for tracking. To have stereo vision, the two monitors should have two different images caused by the parallax of two eyes. A CyberGlove is a glove with 18 bend sensors for hand gestures and a 6-DOF sensor for hand position. These 18 bend sensors can detect the bend angles of joints and a virtual hand can represent the gesture by inputting these angle values.

The Application of COVR

COVR is expected to be used to educate and train our undergraduate students in performing a construction operation without subjecting them to the real hazard of such operations. At this stage a bridge model of COVR is almost completed. A scenario of an application of the model is furnished below:

1. When the program begins, the screen will show a menu which indicates the construction cases implemented in this system. When the user picks one item, assuming that the item is "the overpass on the junction of SR-16 1 and New Albany Road," the virtual site is loaded and images around the user display the ground, the sky, two approach hills, and the pier (Figure 1). The user is now situated in the virtual construction site at the junction of State Route 161 and New Albany Road. The user can begin to look around while standing, and can "walk" or "fly" around to observe the area and observe the characteristics of the construction site.

2. Now the user has to construct the superstructure, which includes girders and the bridge deck. The user can select either steel or pre-cast concrete beams as girders. The system has provided some standard format of girders such as American Association of State Highway and Transportation Officials (AASHTO) Type II, III, IV, V, and VI pre-stressed concrete girders, and American Institute of Steel Construction (AISC) standard steel beams (Figure 1). For example, if "aashto5" is input as the girder type, an AASHTO type V pre-stressed concrete girder will appear in the virtual environment. If "w30x2 11" is typed, the program will look into a data file which restores the dimension information of all AISC steel beams. Moreover, the user can specify how long the girder is. Then these girders should be erected onto the pier and abutments. The user can pick the desired girder and move it around with a mouse, and then place it in a proper position. Some girders which are assembled piece by piece can be simulated as well. In this case, the user can move the two pieces close together and when they touch each other at their ends, they become a completed girder.

3. If the user wishes to review the completed operations and procedures, a recording function is provided to record and playback the movement of objects and view points. This function also allows the trainer to present a default construction procedure. When a construction procedure is playing, the user can still move around to observe the procedure, and at any time stop, rewind, and replay to review a particular sequence.

4. By wearing a CyberGlove, through the virtual hand that comes with it (Figure 2), the user can pose hand gestures to command the computer. For instance, the user can define a forward gesture as pointing the index finger toward the front. Subsequently, in the virtual environment, the user can make this gesture to move forward. Because a user's hand gestures are often unique, and as each user has his or her own preferences to use a specific gesture as a specific command, a gesture recording function is furnished to provide a flexibility in changing the recognition pattern.
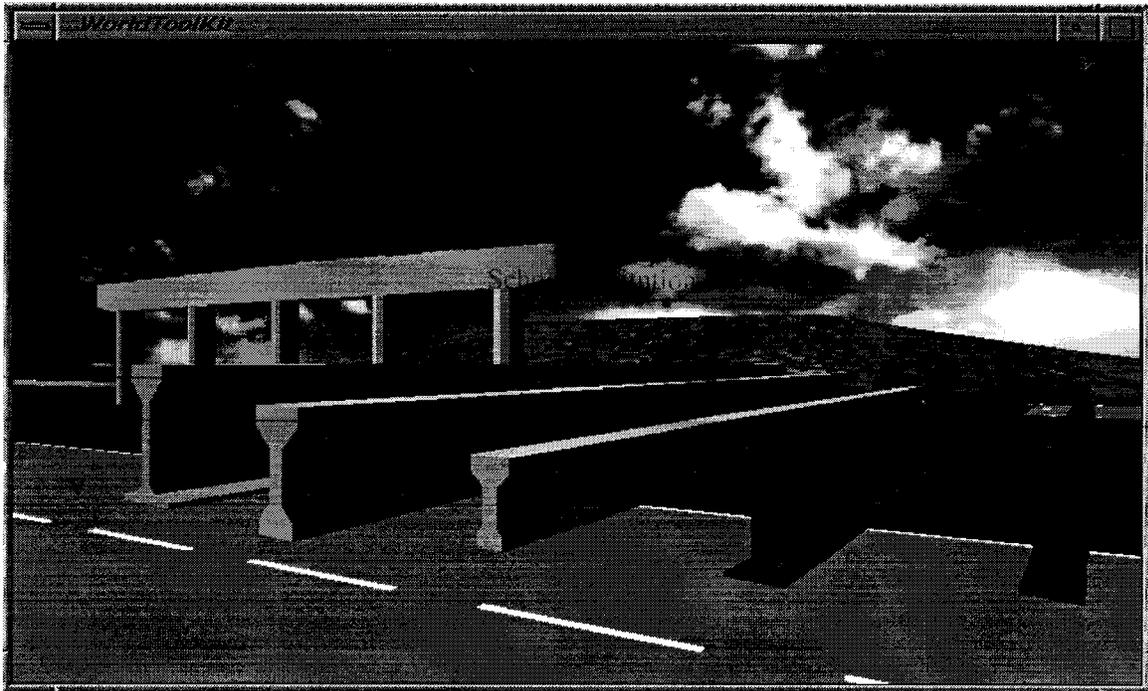
Figure 1. Selection of various types of girders
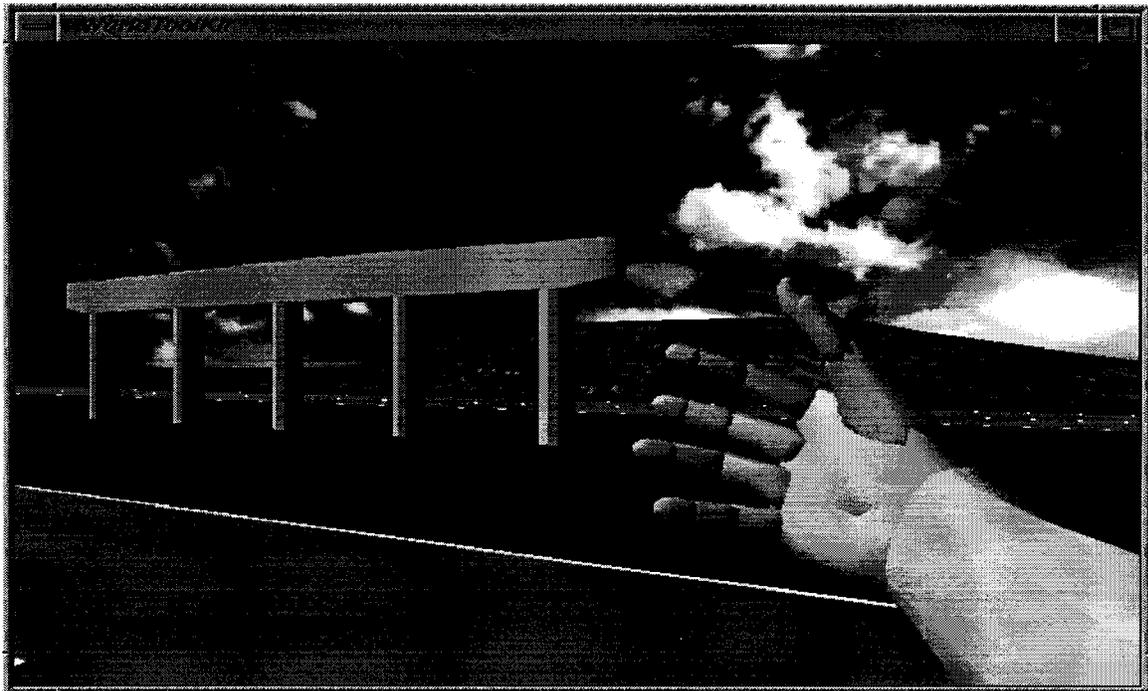
Figure 2. A virtual hand representing the CyberGlove for site operation

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At this stage, we have completed the bridge components and the virtual hand. The final stage in the development of this model is to activate the virtual hand so that it can be used to pick up and drop the girders and beams, place them onto the piers, install bracings, construct bridge deck forms, and pour concrete into the form. All these operations must be performed safely. Unsafe operations will result in audio/visual warnings. Hence, students can learn from COVR model how to build a bridge superstructure the right way without subjecting them to the hazards of the real construction operations. In addition, students can also appreciate the danger of such operations.

After completing the COVR model, we plan to incorporate the model into the undergraduate curriculum of our construction program. We expect that students who take the modified courses will be totally immersed in simulated construction projects. In addition, they will comprehend the multitude of operations involved in a construction proj ect in a relatively short time. Consequently, simulation using COVR is expected to furnish students with a tool to avoid construction and structural problems in their future professional careers.

Conclusion

Inadequate construction education and training impairs the ability of our undergraduate construction students to obtain practicality and feel for engineering construction, knowledge of overall structural behavior, creative thinking and problem solving, accuracy of assumptions made in the design, and engineering judgment. Such impairments have directly or indirectly contributed to construction failures and accidents with the often tragic loss of human lives. As such, the traditional education and training in our current construction curriculum must be enhanced. To overcome this problem, the COVR model is currently being developed and will be integrated into our curriculum.

This model encompasses the erection process of a bridge superstructure--one of the most hazardous construction operations--in a virtual environment. Here, students can simulate the erection stages of each component of the bridge in the laboratory without being subjected to the on-site construction hazards. Students can "participate" in the entire process of erecting a bridge superstructure. Furthermore, through the numerous scenarios furnished by the model, students can learn--in an accelerated way--how to build a bridge the right way and how not to build it the wrong way.

As a final note, while at the beginning the cost of the hardware has often deterred educational institutions from investing in such a simulation tool, we believe that the eventual advantages of avoiding construction failures and accidents far outweigh the initial costs of acquiring such an instrument. In addition, the cost of computers is decreasing dramatically and the speed of these machines is increasing considerably. We expect that in the near future, most colleges will be able to afford a VR system for use in their construction curriculum.

Acknowledgment

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