

Construction of a Virtual Reality Learning Environment for Teaching Structural Analysis

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ABSTRACT: This article discusses applying virtual reality (VR) to civil engineering education. It first describes the difficulties of teaching structural analysis in the traditional classroom setting and then outlines the potentials and limitations of using VR for civil engineering education. A VR-based learning center has been developed for structural analysis curriculum, and its design, development, and evaluation are reported. © 1997 John Wiley & Sons, Inc. *Comput Appl Eng Educ* 5: 223–230, 1997

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INTRODUCTION

Structural analysis is a fundamental subject in civil engineering education. However, students are usually not well motivated to learn this subject, apparently for two major reasons. First, structural analysis deals with high-level abstractions and difficult concepts, such as force equilibrium and force transfer between structural members and their supports. Students have difficulty grasping these abstract concepts. Second, these concepts are difficult to visualize. For example, some students do not understand

why some structural forms are stable while others are not. Moreover, they have a hard time understanding structural potentials for instability, given static, two-dimensional (2-D) wire-frame diagrams printed on paper or drawn by teachers on chalkboards. Without the ability to visualize abstract concepts, students report that they can hardly make sense of the subject matter.

The use of computer technology in teaching structural analysis may provide an alternative that enables presentation of learning materials dynamically. For example, computers can simulate the instability failure patterns of frame structures supported by three parallel rollers when forces are applied in directions perpendicular to those of supporting members, as shown in Figure 1. In addition, with the multimedia capacity of computer technology, printed materials can be supplemented with

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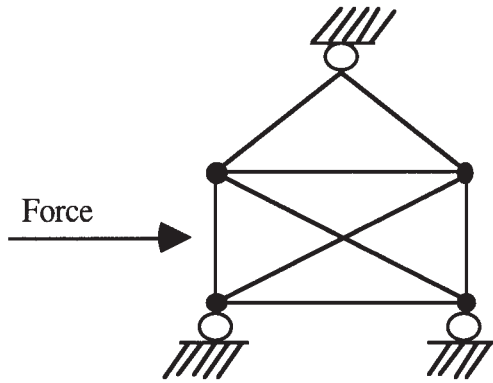


Figure 1 A 2-D frame structure.

2-D or 3-D graphics, video, and animation. Students are thus not only more motivated to learn, but also better able to visualize the concepts [1].

APPLICATION OF VIRTUAL REALITY TO CIVIL ENGINEERING EDUCATION

Recent developments in virtual reality (VR) can be considered a more advanced computer technology, and are attracting more and more attention among people in engineering education. Because of its newness in the computer technology field as well as in the educational field, it is defined differently by each researcher. The most popular and well-known idea of VR is technological: a particular collection of technological components including computers, head-mounted displays (HMD), headphones, and motion-sensing data gloves [2]. Another definition of VR is more functional, focusing on real-time interactivity: “a simulation in which computer graphics is used to create a realistic looking world . . . the synthesized world is not static but responds to user inputs” [3]. A third view is more experiential and psychological; Steuer [4] defined VR as “a real or simulated environment in which a perceiver experiences telepresence.” Telepresence, in this sense, refers to the extent to which one feels present in a computer-mediated environment, as well as in the immediate physical environment.

Educational applications of VR can make use of the threefold definition mentioned above. VR consists of computer technology-based artificial worlds filled with computer-generated images that respond to students’ movements and inputs, and which allow students to experience a mediated sense of presence. Students in such computer-generated learning environments can interact with information, move

around, manipulate virtual objects, and have a sense of actually being there.

The potentials of VR for education have excited the researchers for several reasons. First, VR can provide an environment for constructive learning [5]. Students are granted high degrees of control over their self-paced navigations through virtual environments. Students are required to be not only actively involved with, but also interactively involved with their environments; therefore, each student has unique learning experiences.

Second, VR has the potential to move learning from reliance on text-based materials to reliance on imagery and symbol-based materials [6]. The visualization of data, especially abstract science and engineering data, may help reduce frustration among students.

Third, VR provides a more direct and natural way for students to interact with the learning environment and objects [7]. Given the above example of a form on three roller supports, students can only imagine its instability when the diagram is drawn on the chalkboard and explained by the instructor. Students interacting with computer courseware on the same subject matter can use a mouse or keyboard to apply directional force to the computer-generated structural form, and observe the results via computer simulation. In VR, students can grab or push virtual structural forms and feel the immediate reactions of those forms.

Fourth, in the VR environment, the participant and virtual objects are not constrained by physical realities or practicalities, such as physical positions and speeds, or forces and displacements. Loftin and colleagues [8] developed a virtual physics laboratory to help college students understand complex concepts such as Newtonian and quantum physics. Students in this laboratory can conduct experiments involving measurements of pendulum oscillation periods not only by changing their length, as in the real world, but also by changing the value of gravitational acceleration, which cannot be done in a real laboratory.

Fifth, the presentation of information in a VR environment allows radical changes in the relative sizes, time, and distance of the participant and virtual objects [5]. In the real world, we can only take a human viewpoint in interacting with the real objects in our environments. However, we can interact with virtual objects from different perspectives, in different sizes, and on various time scales in VR. For example, a student can take the viewpoint of a human inspector in checking for cracks in a bridge pier from the outside, and change instantaneously

to the viewpoint of a termite seeing the cracks from inside the pier. In VR, students can safely experience their buildings collapsing in a 15-s earthquake in real time, or compress the collapsing process to 5 s, stretch it to 45 s, or even freeze or reverse the process.

In sum, the VR environment allows participants to have these knowledge-building experiences that are not available in the real world; therefore, it has invaluable potential for civil engineering education. However, VR has some limitations and down sides that must be mentioned here.

The first is the cost of VR systems—of hardware as well as software—as well as the cost of course developer's expertise. These price constraints make VR nowadays an infeasible instructional technology for teachers to adopt in their regular school curricula. However, prices are expected to drop as the technology advances and more applications are developed.

The second limitation is its equipment use [9]. For example, HMDs are too heavy for some people. The wires connecting the HMD and data gloves to the computer are quite cumbersome and may get tangled. The HMD and the wires limit to some degree the free movements and gestures of the people wearing them. However, as HMD materials and wireless technology advance, usage problems are expected to resolve themselves.

The third limitation is that some people may become disoriented when they take the HMD off. Therefore, an HMD-equipped VR learning environment may not be suitable for every student.

DESIGN AND DEVELOPMENT OF VR LEARNING ENVIRONMENT

Development Platforms and Tools

The world of VR consists of many virtual objects. Each object is made from models and attributes. Models describe its outside appearance, while attributes define its interactivity and reactions. To build virtual objects, special tools and platforms are required.

Two platforms were used in this study to build the structural analysis VR learning environment. Models of virtual objects were built on Pentium 90 computers, using Autodesk 3D Studio software. The attributes were defined on an SGI Crimson/VGX computer, using the Division dVISE program. The reason for building objects on different platforms is based on the specialties of the software used. dVISE

Table 1 Hardware and Software Used to Develop and Play Back the VR Learning Environment

Computer platforms
IBM-compatible (Pentium 90 CPU)
SGI Crimson/VGX
Development software
MS-DOS 6.2
Autodesk 3D Studio R4
UNIX System VR 4.0
Division dVISE
Display platform
SGI Onyx/RE2
Display and control devices
Division HMD
3-D mouse

allows the designer to define object attributes efficiently, but does not build models. On the other hand, 3D Studio has a powerful capacity for building and modifying models.

The playback platform consisted of an SGI Onyx/RE2 computer, a Division HMD, and a 3-D mouse. Table 1 lists the hardware and software used to develop and play back the VR learning environment.

DESIGN OF LEARNING ENVIRONMENT AND INFORMATION PRESENTATION

To build a VR learning environment, a real-world metaphor is needed first to guide the design of the environment and objects. The metaphor for this study was a three-floor learning center that provides students a place for learning by doing. Students were expected to learn or reinforce their knowledge of structural analysis by manipulating learning objects and information provided by the learning center.

The building elements of the VR learning center included the floor, divider, elevator, hallway, and baseboard. The floor of the center can be thought of as a chapter in a book. Each floor has several dividers that separate spaces in which related concepts are demonstrated, equivalent to sections of a book chapter. Students can use a virtual elevator to move to other floors, and use the hallway to enter each divided space at will. The colored tiles on the floor are designed to help students differentiate the spatial relationships between learning objects and their own positions in the learning center. Students can determine how far away an object is by the relative size of the tiles; that is, the farther away an

Table 2 Building Elements and Their Metaphorical Meaning or Function

Building Elements	Function or Metaphorical Meaning
Learning center	Self-study guide
Floors	Book chapters
Floor numbers (1, 2, 3)	The learning content depth (the higher, the deeper)
Dividers (on the second and third floors)	Sections of book chapters
Elevator	Move between chapters
Hallway	Move between sections
Color tiles on floor	Help learners orient themselves in the virtual space
Baseboard	To help learner distinguish between the horizontal floor and the vertical wall

object is, the smaller the tile is. The baseboard helps learners distinguish between the horizontal floor and the vertical wall. The design of each building element and its mapped function or metaphorical meaning are listed in Table 2. The floor plans are displayed in Figure 2, and two scenes from the center are demonstrated in Figures 3 and 4.

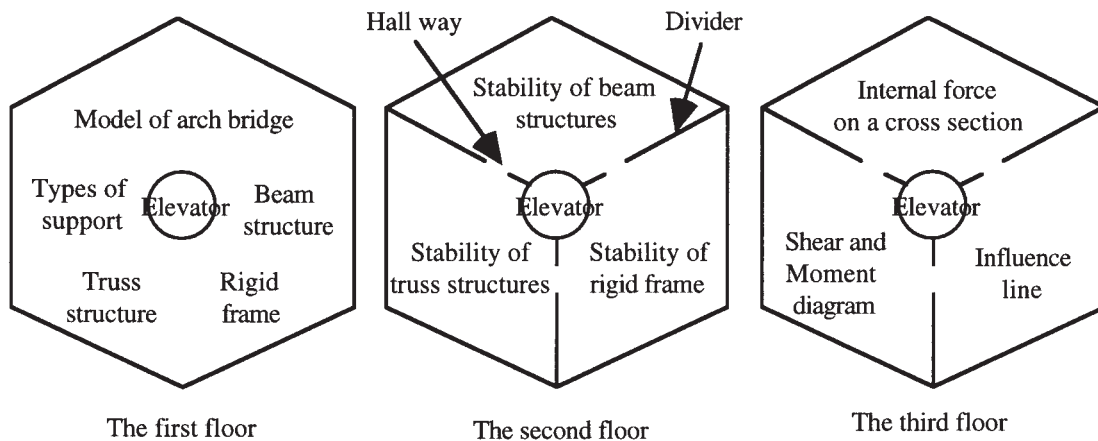
There is no preset order or time limitation on student navigation within the learning center. When students enter the learning center, they are located in the elevator stopped at the first floor. Students can walk out of the elevator or go to other floors to start their learning journey. On each floor and divided space, students can interact with learning objects by movements of touch and grasp. In this VR-based learning center, a hand-shaped model represents the user's real hand, as demonstrated in the center of Figure 3. When this hand-shaped model collides with any learning object, the action of touching happens. Because the current system does not provide tactility, touch feedback changes the color of touched objects. In other words, visual feedback is used to replace the tactile feedback for

the action of touching. When a users touches a learning object, they can perform the action of picking up by pressing a 3-D mouse button or using a data glove gesture.

A caption on the wall of each divided space indicates the learning content topic. However, text displays are used very sparingly in the learning center, for two reasons: First, the HMD resolution is limited, which makes it difficult for students to read small word displays. Second, the letters are made of polygons in virtual reality; thus, word displays require immense numbers of calculations. Too many such text displays would delay all other system operations. The principle of parsimony is also applied to the interior design of the learning center. To increase system efficiency and avoid distracting students' attention, the interior design does not emphasize the visual realism of the center. There are no unnecessary decorative objects in the center.

Design of Learning Content and Objects

The learning contents and objects displayed on the first floor are support types, structure types, and a

**Figure 2** Floor plans for the VR learning center.

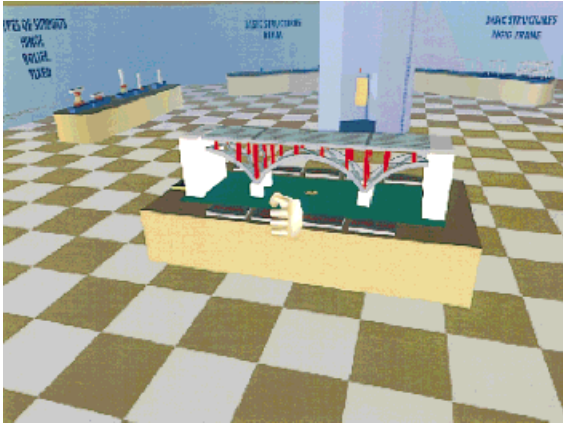


Figure 3 Scene from the VR learning center, showing support types, structure types, a sample structure of an arch bridge, the elevator, and the hand in the middle.

sample structure, as shown in Figure 3. The supports and structures are constructed using typical structural analysis symbols, as indicated in Figure 4. The learning objects are located on tables. Students can observe the objects from all directions. Object names are displayed when the student's virtual hand touches them; when the objects are released, the names disappear. This design allows students first to familiarize themselves with the appearances of supports and structure, and then to learn their names. When students pick objects up, they may rotate or deflect them, or allow them to remain fixed, depending on predefined structural attributes.

The sample structure is an arch bridge located on a table. Five buttons labeled Abutment, Arch Rib, Column, Deck, and Diaphragm are located beside the bridge. When students press (pick) any button, its mapping component to the bridge

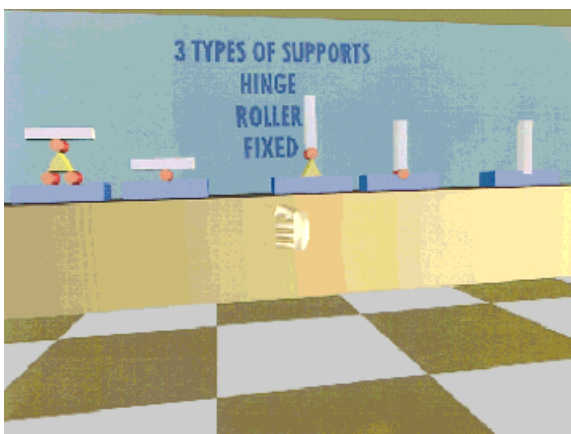


Figure 4 Scene from the first floor of the VR learning center, showing three types of supports.

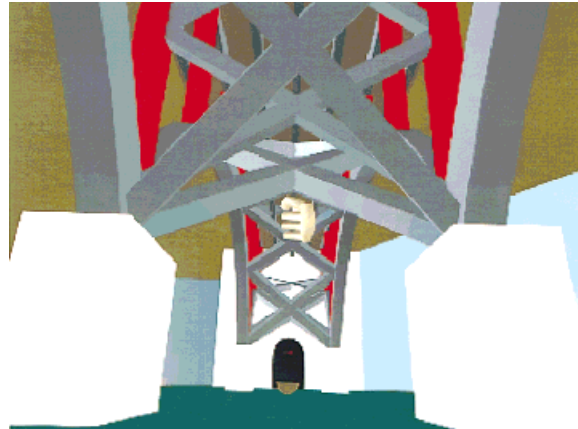


Figure 5 The student can be in a boat to observe the arch bridge from underneath.

changes from gray to red. This design allows students to observe the various components of the bridge and learn their names. An in-boat button is located at one side of the bridge. When students press this button, they seem to shrink and are moved to a small boat underneath the bridge, as shown in Figure 5. The boat will then take the students under the bridge, allowing them to observe the bridge from underneath. This design takes the advantage of VR's ability to resize and relocate users within the VR environment, as suggested by Winn [5] and Stuart and Thomas [10].

The learning content on the second floor consists of determining the structural stability of various structures. This floor is divided into three spaces in which a total of 21 learning objects are demonstrated: beam, truss, and rigid frame. Before students touch or pick up these objects, the objects

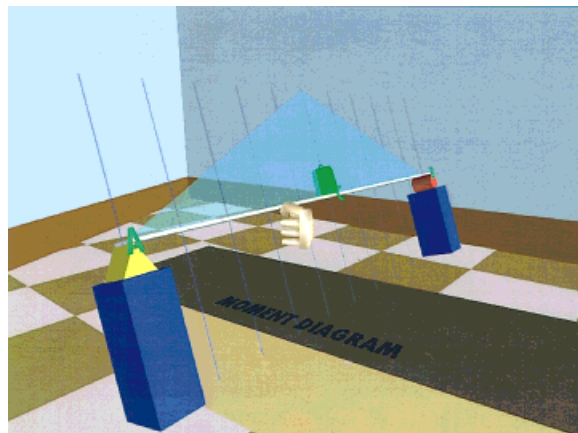


Figure 6 Scene from the third floor of the VR learning center, showing the weight placement on the beam and the corresponding moment diagram.

remain stable, since no external forces have been applied. If an object is naturally stable, it will not react to student manipulations. If an object is naturally unstable, it will be deformed or rotated by students' manipulations. Students must actively interact with these learning objects; otherwise, they will not be able to learn their stability characteristics.

The learning content on the third floor includes the concepts of internal force on cross sections, moment diagrams, shear diagrams, and influence lines in structural members under prescribed loadings. The internal forces on the cross section of a structure include shear force, axial force, moment, and torque. When any one of the four internal forces is applied to the structure, the deformation caused by the force is displayed. When the student presses the Plus button beside the square-shaped block structure, a red arrow representing the force is directed outward on the longitudinal axis of the block, and the block member is lengthened. When the opposing Minus button is pressed, a red arrow representing a force directing inwards appears, and the block member is shortened.

The design for showing structural deformations caused by biaxial moment and torque forces is somewhat different. Because these deformations are 3-D, the deformed block structure is designed to rotate slowly above the table, allowing students to observe the block from different angles.

To help students visualize shear force and moment, a simply supported beam and a cantilever beam are placed on the table. Each beam is divided into 10 equal segments, and a standard weight is placed on the beam. When students move the weight along the beam, corresponding shear and moment diagrams are demonstrated, as shown in Figure 6. This design allows students to visualize the relationship between weight placement on the beam and the corresponding shear force and moment resulting from it.

The design for visualization of influence lines is similar to that for shear and moment diagrams mentioned above. When the student grasps the standard weight on the beam, a rectangular bar representing the degree of loading on this spot on the beam is demonstrated. In other words, the height of the bar varies depending on the amount of weight applied to the various spots on the beam.

EVALUATION OF THE VR LEARNING ENVIRONMENT

A formative evaluation was conducted to examine the usability and instructional effectiveness of the

VR learning center. Two major evaluation approaches were adopted: expert-based and user-based [11]. Two experts were involved in the evaluation. One experienced civil engineering instructor who has been teaching structural analysis for 6 years was invited to check the correctness of the learning objects and their behavior. The learning materials were then revised according to his evaluation. One experienced human-computer interface (HCI) expert was invited to provide opinions on the usability of the learning environment. The method was to have this HCI expert think aloud while she walked through the center. An in-depth interview was also conducted after she finished her journey in the VR learning center. Suggestions from both experts, along with the students' evaluation results, are reported in the next section.

Seven sample target learners participated in the user-based formative evaluation. Reiser and Kegelmann [12] stated that evaluation of a learning system is incomplete without a report on student learning performance. Therefore, a written comprehension test was conducted before and after each student finished the journey. The test consisted of three types of questions: knowledge, comprehension, and application. The test scores indicated that students acquired basic knowledge of structural analysis from the center. The test results will help the designers identify and revise ambiguous parts of the learning environment and objects. Each student's tryout was videotaped, and an in-depth interview was conducted after the tryout.

SUGGESTIONS AND CONCLUSIONS

Based on the experience of developing the structural analysis VR learning center and the results of its formative evaluation, suggestions are provided for both the interface design and learning materials presentation, as follows.

The following helped students navigate through the VR learning center and interact with learning objects:

1. Providing floor plans and a tracking map to reduce the possibility of students getting lost in the VR learning center. Floor plans, such as those in Figure 2, should be posted somewhere in the center. A tracking map that keeps students informed about where they are helps orient them. Several students also requested a Home function that would automatically re-

- turn them to the entry point: that is, inside the elevator stopped at the first floor.
2. Providing students with rich information about spatial relationships in the VR center. For example, using floor tiles and light sources to help students determine the relative distances between themselves and objects, and from object to object.
 3. Providing a flexible spatial scale for student movements. For example, when students walk along the hallway, their movements can be on a larger scale, enabling them to walk quickly to desired learning objects. When they get close to the tables where the learning objects are located, their movement should be slowed, so they can easily and delicately perform touching or grasping movements.
 4. Providing appropriate constraints on the environment and learning objects to increase realism. For example, floors, dividers, and tables should be defined as impermeable.
 5. Replacing tactile feedback with audible or visual (e.g., thumps, color changes) feedback when students touch or grasp learning objects, when tactility is not available, as in the present study.

For students to learn more efficiently in the VR learning center, we suggest the following:

1. First-time students be allowed to enter the VR learning center at least twice, with a short break between visits. The first time allows students to practice moving and manipulating in the VR world. The second time allows them to focus on the learning objects they are supposed to interact with. This suggestion came from the evaluation experience that students spent 5–10 min familiarizing themselves with the environment, out of an average of 25 min navigating in the center. Since 30 min is probably the maximum time ordinary students can wear the HMD while navigating through the virtual world in a single sitting or session, spending too much time familiarizing themselves with VR leaves them no time to perform learning tasks.
2. Given the limitations on system calculation capacities, performance speed should be considered more important than realism of center interior design. The more objects or textual displays existing in the virtual world, the more calculations are needed, and thus the slower the system performance will be. Use of the

principle of parsimony worked in this design. In the formative evaluation, students did not complain about the speed of the system or the realism of the interior design.

3. Take full advantage of 3-D display abilities as well as the flexible-scale capacity of VR to demonstrate the learning objects. The arch bridge in this study is the best example, and was most welcomed by the students.

Based on the prototype VR learning center for structural analysis presented in this study, three recommendations are proposed for future research:

1. In this study, paper and pencil tests were given to students before and after their learning journeys through VR. In the future, an innovatively formatted test can be disseminated right in the virtual learning center.
2. In this study, we encountered difficulty in trying to display a large amount of textual information. As mentioned earlier, because of limitations on the HMD display resolution and system calculation capacity, as little textual information as possible was displayed in the learning center. However, some textual information such as mathematical equations is indispensable for learning structural analysis. How to display large amounts of textual information in VR using current VR technology development techniques is a problem that needs solving.
3. More students should be invited to participate in the evaluation of the design and development of the VR learning environment. Empirically derived information on system functionality, learning objects, user-interface design, and learning experience is needed to guide the quantitative and qualitative development of educational applications of VR.

SUMMARY

In this study, a learning center was developed to examine the feasibility of applying VR to civil engineering education. It is believed that the use of VR will encourage development of even newer methods, tools, and environments for instruction and learning. The promise VR provides is exciting and its expected impact on civil engineering education will be immense. Furthermore, VR brings us new perspectives for research, not only into the technologies themselves, but also into the philosophy, strate-

gies, and tactics of instruction and learning. It is expected that more research on the applications and more interactive VR-based learning systems like the one in this study will be developed to benefit all civil engineering students.

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BIOGRAPHIES



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