Cognitive Scaffolding in Web3D Learning Systems: A Case Study for Form and Structure

Felipe Bacim[*], Nicholas Polys[†], Jian Chen[‡]
Department of Computer Science
Virginia Polytechnic Institute and State University
University of Southern Mississippi

Mehdi Setareh[§], Ji Li, Lee Ma
School of Architecture + Design
Virginia Polytechnic Institute and State University

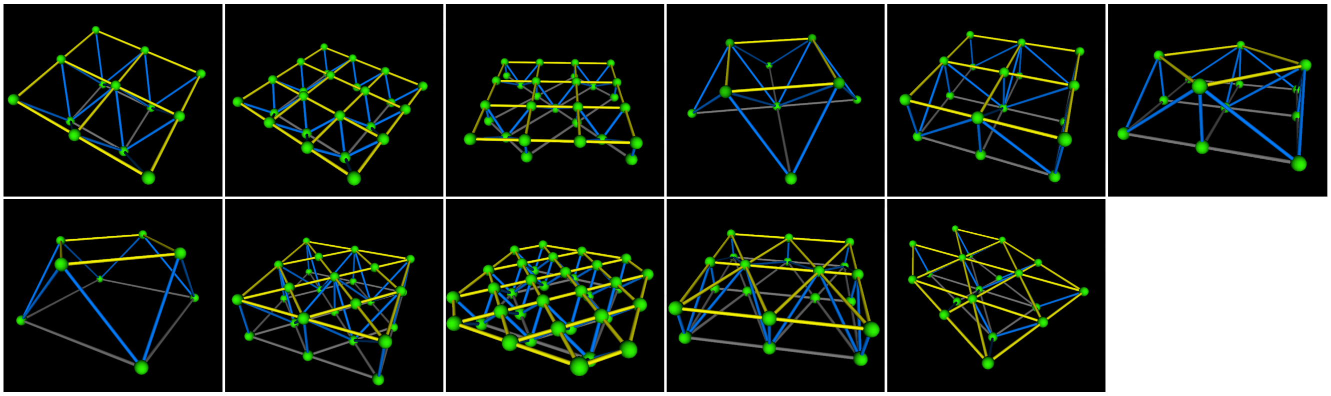


Figure 1: *The eleven base structural units for long-span space frames in SAFAS.*

Abstract

In this paper, we describe a case study in usability engineering for Web3D learning systems and introduce a new step to the typical methods of the usability design. Pedagogical applications present a challenge to the usual usability engineering process in that the end-users of the system (students) cannot describe the requirements of the system. For this situation, we engage the latest evidence and principles of cognition to help map requirements to information design for an interactive learning system.

Our system seeks to improve the structural understanding of architects and to teach relationships between form and structure in long-span systems. We provide both explanatory multimedia resources and interactive resources including a Web-based modeling and simulation tool that aids architecture students with better understanding of the relationship between structure and form in design. We describe our design process and the system and examine the qualitative impact of the cognitive ergonomic process. This extra step in the usability design process of mapping expert knowledge to human perception and cognition can increase awareness of the requirements of a learning system and improve the effectiveness of the subsequent design.

CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—Human information processing;
H.5.2 [Information Interfaces and Presentation]: User Interfaces—User-centered design;

Keywords: Usability Engineering, Web3D Learning Tools.

1 Introduction

Next-generation interactive learning systems are using virtual environments and simulation as a tool for communicating engineering concepts and improving knowledge acquisition. Chittaro [Chittaro and Ranon 2007] showed the pedagogical basis for using Web3D technologies as an educational tool, and also states that educational virtual environments can provide experiences which are impossible to try in the real world because of distance, cost, danger or impracticability. Furthermore, Web3D technologies allow these environments to be accessible anywhere using a computer connected to the Internet.

Structural engineering applications targeted to students concerns communicating concepts such as load and stress distribution, connections between members and nodal member displacement. They also must provide information about how structure units are formed and how different geometric shapes are used to form the specific configurations of spatial structures because students must be able to understand the relationships between form and structure. Figure 1 shows some of the different structure units students have to learn about.

Munro et al. [Munro et al. 2002] outlined the cognitive processing issues in virtual environments by the type of information they convey (Table 1). In reviewing VE presentations and tutoring systems, the authors note that VEs are especially appropriate for: navigation and locomotion in complex environments, manipulation of complex objects in 3D space, learning abstract concepts with spatial characteristics, complex data analysis, and decision making. In our case

---

[*] e-mail: {fbacim}@vt.edu
[†] e-mail: {npolys}@vt.edu
[‡] email: jian.chen@usm.edu
[§] e-mail:setareh@vt.edu

Table 1: *Munro's Taxonomy of Knowledge.*

Location Knowledge	**Structural Knowledge**
Relative position Navigation 'How to view' (an object) 'How to use' (an object's affordances)	Part-whole Support-depend (i.e. gravity) Containment
Behavioral Knowledge	**Procedural Knowledge**
Cause-and-effect Function Systemic behavior	Task prerequisite Goal hierarchy Action sequence

study, Structural and Location knowledge refers to nodes and members, and how they are related. Behavioral knowledge is about how our system responds to users actions and different structure patterns are shown. Procedural knowledge is related to assembly sequence and how structure units are generated.

Our main challenge for the requirements analysis and for the information design is that the stakeholders that are providing us with the requirements are experts (professors); whereas the end users of our system are novices (students) and do not really know the requirements of the system. In order to correctly address this problem, we need to look for answers to questions such as: how do we get what novice users really want or need when they do not know what they want or need? How do we use the information provided by experts and make sure novices will be able to learn that? How to design the system to adapt to the characteristics of the learners and how to evaluate such effects? How to compare the web-based setting with the real-world classroom-based setting? By addressing these issues, it may be possible to improve the usability engineering process for educational tools.

This paper focuses on the development and the application of this method in the design of our project, and is organized as follows: Section 2 presents background for the development of our method; Section 3 describes the method; Section 4 describes the case study and how we applied the method we developed; Section 5 presents the system design and architecture of our case study; Section 6 is a presentation and discussion of initial results and Section 7 presents future work.

2 Background

This section is divided into two parts: similar applications, which will present some examples of educational applications of VR and Web3D; and perception and cognition, which will present some of the work for our structural engineering and design case study.

2.1 Educational Applications

The ScienceSpace Project, presented by Salzman [Salzman et al. 1999], is used as case study in the development of a model to understand how virtual reality can aid the learning process of complex concepts in a science education virtual environment. It included modules for learning about dynamics and interactions for the physics of Newton, Maxwell, and Pauling. This application illustrated that immersive virtual environments can aid learning of complex concepts by their spatial, 3-dimensional aspect, by their support for users to change their frames of reference, and the inclusion of multi-sensory cues. It seems likely that this advantage would also transfer to desktop courseware and applications.

Education researchers have shown improved student performance by augmenting science lectures with desktop virtual environments including the 'Virtual Cell' environment for biology and the processes of cellular respiration [McClean et al. 2001]. A different example on using VR as an educational tool is provided by the Virtual Big Beef Creek project [Campbell et al. 2002], in which Web3D standards were used to develop a collaborative learning interface for ocean science. With this interface, users are able to navigate and collect information in a data-rich representation of a real-world estuary. This way, users are able to have a better sense of the overall watershed before they venture out to experience it in person.

Liarokapis et al. [Liarokapis et al. 2004] present another Web3D educational application that allows users to interact using virtual and augmented reality (AR) to evaluate the potential benefits of Web3D and AR technologies in engineering education and learning. Four mechanical engineering themes are presented: machines, vehicles, platonic solids and tools. This work is similar to ours because it is also divided into a knowledge base organized by themes, and an interactive visualization, in which students use 3D graphics to interact with and learn about these themes.

There are a number of Web3D frameworks that support simulation as a service over the web. IRVE-Serve for example, uses common HTML and scripting technology with X3D to expose server-side simulations and results over the web [Polys et al. 2007]. In the domain of architectural design, Bowman et al presented the application Virtual-SAP (Structural Analysis Program). It allows architects visualize building structures and their responses to environmental conditions such as earthquakes in a virtual environment [Chen and Bowman 2009]. It seems clear that architects can use VR as a tool to learn about the structural behavior on desktop and on immersive systems; we aim to deliver an architectural design and structural engineering tool to students across platforms and the web.

2.2 Usability Engineering

Usability Engineering methods, such as Scenario-Based Design [Rosson and Carroll 2002], are iterative models for designing user interfaces that encompass analysis, design, and prototyping and evaluation. For this paper, we focus on the analysis and design stages. In the analysis stage, the needs of the stakeholders of the project are determined and analyzed, and the requirements specification is generated. The design stage is divided into three parts: activity design, information design and interaction design. In the activity design phase, the concepts and services of the new system are specified, in other words, the system functionality. In the information design phase, engineers define how information is presented to the user and study how users perceive that information, and help to increase and facilitate perception and understanding of the information. The interaction design phase is the specification of how users access and manipulate information.

Usability engineering and design methods are meant to be generic, however research has shown that virtual reality requires some special considerations [Hix and Gabbard 2002]. In designing learning systems, usability engineers have to overcome a number of challenges for requirement analysis and information design that may not be best represented by generic usability design methods. A typical challenge to the usual usability engineering process is the fact that end users are not necessarily aware of the requirements of the system. In this case, usability engineers may derive their requirements through any number of techniques such as ethnography and knowledge elicitation (interviews) with stakeholders. Such a situation is even more profound when designing for novices and students.

In order to address these issues, a domain-specific design can be used. According to Chen [Chen and Bowman 2006], domain-specific design is to design a user interface with a specific application or domain in mind. This type of design is used to improve the usefulness of the interface. In the example presented in [Chen and Bowman 2006], generic interaction techniques were used in a design tool with limited success. To overcome this problem, a 'domain-specific' design process was used to develop new interaction techniques. In our project, we adopt a similar specificity to the case of a structural engineering learning system - we are building an interactive web-based modeling and simulation tools for architecture students. Our tool is targeted to enable a better understanding of the relationship between structure and form by applying engineering analysis techniques (numeric simulation) to spatial structure systems.

2.3 Perception and Cognition

In this section, we present a set of concepts from the literature on perception and cognition. The challenge for eLearning designers is applying research psychology into design guidance. We demonstrate the relevance of these concepts for a structural engineering and design application.

Wickens [Wickens 1992] suggests a few different components of virtual reality that are connected to and can affect learning: dimensionality, motion, interaction, the frame of reference, and the use of multimodal interaction. Wickens and Hollands [Hollands and Wickens 1999] argue that we recognize stimuli in the environment because most of our recognition is based on the combination of two or more stimulus dimensions. They divide this multidimensional stimulus into orthogonal, which refers to when the dimension is independent of others, and correlated dimensions, in which the stimulus level of one dimension affects the others. They emphasize this distinction between integral and separable pairs of dimensions, which is similar to orthogonal and correlated dimensions but refer to the physical form of the stimulus and not the properties of the information conveyed in each dimension. For instance, height and width of a rectangle are integral dimensions, while the size and brightness of an object are separable dimensions.

The Gestalt principles address the criteria for the perception of unity and grouping of figures (see [Ware 2000]). These principles are crucial when considering the design of multimedia environments, and the possibility of 'chunking' visual items and features. This is an important part of our case study as it helps us understand how to display several dimensions of information to the students.

On a study on visual Working Memory (WM), Vogel et al. [Vogel et al. 2001] found evidence that WM capacity should be defined in terms of integrated objects rather than individual features. They show that subject's WM could store three to four objects, and that complex objects do not require more capacity than simple objects. However, they do not argue that three or four items of high-fidelity are necessarily represented WM; in fact they admit that WM may contain more items of low-fidelity representation. Presenting a similar argument, Biederman proposed simple geometric shapes, such as blocks, cylinders and cones, as fundamental units of shape in object perception [Biederman 1987]. In addition, Irani and Ware [Irani and Ware 2000] showed that using such 3D primitives to display information structures was significantly better for substructure identification than in displays using 2D boxes and lines. Findings like these helped us define how different structural units are presented in our interactive online tool.

3 Method

The two main issues we found when using the typical usability engineering method as applied to learning systems are: cognitive concerns are hard to apply and there is little guidance on how to apply psychology research results in practice. Secondly, the ultimate end users (students) do not know what they need to know. Our method aims at improving the usability design process to overcome these issues.

As we have shown in the Background section, HCI methods propose to take into consideration the processes of perception and cognition, however, it is still difficult to use in practice. We propose an addition to the usability engineering process when designing a learning system: to take the information provided by the domain experts (professors) and map them to perception and cognition processes after the requirements analysis and during the information design stage. The concepts in this case are specific to the application domain. Other domains or even other tasks in the same domain (e.g.: structural design and artistic design of buildings) can use different concepts.

This leads us to our second concern, which refers to the fact that professors are the stakeholders that provide the information we display. This is a problem because the users of a learning system are the students, not the professors. In our usability design process, we have to make sure that the information provided (instructional content) is understandable by novices.

In order to solve this, we developed a three-step solution to map the requirements to information design. The first step is to determine the requirements in terms of instructional content that the students need to learn about. In a Scenario-Based Design, this would be done in the requirements analysis stage. The second step is to map the content to perception and cognition concepts in order to find the ones that can better represent the knowledge students will use to learn the content. This second step we are adding to the traditional usability engineering method, and is the main contribution of our work. In a Scenario-Based Design, this step would fall in the information design stage. The third step is to apply these concepts to generating a visual representation. With these steps, the information design stage of an educational tool becomes not only easier, but also more focused to the learning goals.

To better demonstrate how this method can be used in the design of learning systems, we will first describe the project in which this method is manifested, and then we will show how this proposed method is being used. Even though the instructional content we are using is specific to the application we show in the next section, we suspect this method can be applied to other learning systems.

4 Case Study

The project we describe is an online learning tool called Structure and Form Analysis System (SAFAS). Current architectural design software cannot be used as effective learning tools because they are designed for professionals and do not provide basic information on how various forms can impact structural performance (and vice versa). They do not provide a true understanding of the interactions of structural and non-structural elements, and they are not adopted for use in immersive virtual environments.

Our solution to overcome these problems is to create an integrated set of computer-aided, web-based learning modules to teach fundamental concepts in structural systems to architecture students with a domain-specific design. The SAFAS consists of two sub-modules:

- **Explanatory Resources:** This multimedia knowledgebase provides explanatory information on various aspects of spatial structure systems. The resource included in this sub-module covers topics such as background and historical development, various advantages and disadvantages, systems, assembly and erection, and case studies.

- **Interactive Resources:** This component helps students to experiment with the structural modeling and preliminary design of spatial structures, as well as the post-processing of the structural analysis results in the form of animated structural models and color-coded element stresses. This is an extension of the Virtual Structural Analysis Program (VSAP) software [Chen and Bowman 2006]. Both desktop and computer-assisted immersive virtual environment (VE) versions of this sub-module will be developed.

In the development of this project, we hope to foster the education of: (a) students by improving their ability to integrate structural systems into architectural designs, and (b) instructors by improving their technical knowledge. With the ability to view a variety of design possibilities immediately, users will be able to work through many different types of design problems much faster and easier than would be possible otherwise. Having the ability to observe and compare the similarities and differences of the deformations and stresses of the structural members across diverse design conditions will improve the user's understanding of relationship between structure and form and his/her ability to transfer these skills to other design problems in the future.

As mentioned before, the stakeholders that participated in the requirement analysis and design stages were not students, but the professor. During the requirements analysis we could only specify what students need to learn by using the system. During the information design phase, we needed to map what students needed to learn to visual representations. To accomplish this, we developed the method described in Section 3.

By enumerating the cognitive material and concepts needed for learning in step 2, designers have concrete rationale for choosing mappings. For instance, behavioral knowledge (i.e. Table 1) can be portrayed with a variety of visual representations; if the student is learning about forces of stress in a member, there may be a number of appropriate visualizations. First, a designer may map quantitative values to color. Without our method, the designer may choose any number of color spaces and mapping functions. Using our extra cognitive step, we can realize that the range of data values should not be considered homogenously. Instead, we note that compression and tension of members are two sides of the same coin and so should be mapped to separate spectral ranges (red vs. blue) but with equivalent mapping functions (intervals).

The application of this method to the system described here is shown in Table 2.

5 System Design and Architecture

The target user group for our Web3D application is junior-year architecture students in a studio course who need to gain an understanding of structural engineering concepts and their relationships to their design forms. Interactive 3D visual design tools provide an exciting mechanism to explore a design space; iteration with validated structural physics simulation can provide direct feedback on the outcomes of design decisions. Ideally we can provide a tight loop between the generative and reductionist design phases.

Our system targets undergraduate students across several universities, each with their own range of computing platforms and operating systems. A typical range of students' personal computers include for example: tablets, laptops and workstations running Mac OS, Windows and/or Linux. The labs contain touch tables, tiled displays and stereo walls and a variety of input devices and tracking systems. In order to minimize installation and maintenance issues across such diverse clients, we have built a web service-based infrastructure (including user directories, submission system and SAP simulator) and a Java and X3D based client.

Table 2: *Mapping of the domain-expert knowledge to human perception and cognitive processes for students.*

Architects	**Human (perception and cognition)**	**Information design**
Structural units (members, nodes)	Structural knowledge [Chittaro and Ranon 2007]	Members, nodes
Understanding how different units are formed	Shape recognition [Biederman 1987] [Irani and Ware 2000]	Member & node types, configurations
	Working Memory [Vogel et al. 2001]	Display the basic geometric shapes that form a unit
Loads, Stresses and Forces	Behavioral knowledge [Munro et al. 2002] Multidimensional judgement [Hollands and Wickens 1999]	Color, shapes
Nodal Displacement		Size, location, orientation

In the typical usage scenario, a student launches a local Java-based application. Through a graphical user interface, the student can select the base unit to use, the span's length, width, structural depth and support locations. The structure is then generated and displayed in the X3D window. The model can be saved at any time and a reduced-order computation of stresses can be applied within the program. When the student is ready to run a full simulation on their designed model, they login and submit it so the SAP server. Their results are available to download and view, continuing their design process. The diagram in Figure 2 illustrates the system architecture.

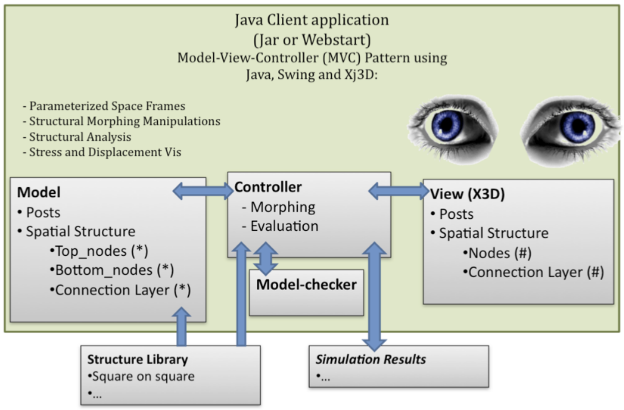
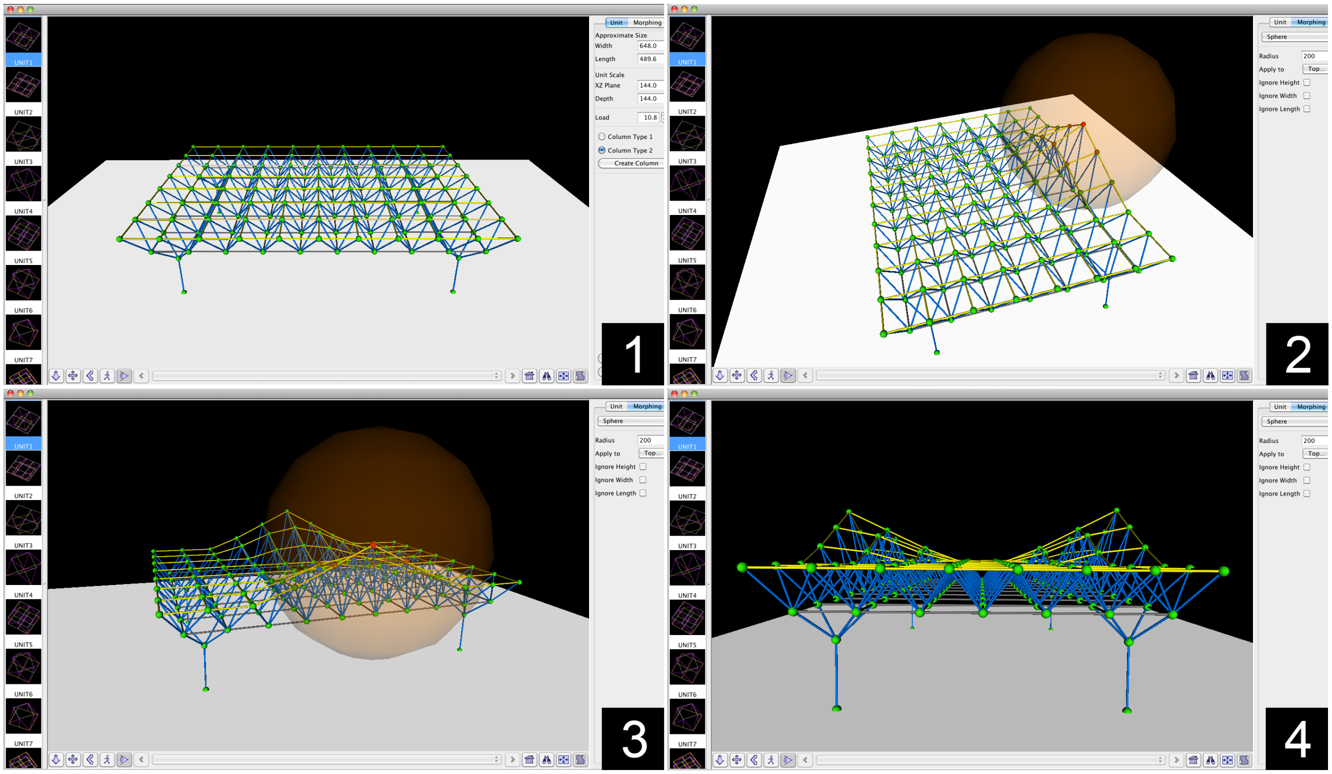


Figure 2: *View Controller pattern in SAFAS.*

Users can navigate around the model, selecting items for add or remove, get details and manipulate. For manipulation, we provide a direct manipulation (3-D) tool coupled with the view program to provide feedback throughout design iterations. We also provide a sphere of influence manipulator to deform the spatial structure, in which a center nodal point for the sphere is selected and manipulated, and all the other nodes that are inside the sphere also receive a fraction of the manipulation performed on that sphere. Figure 3 shows the sphere of influence and how it can morph a structure frame in SAFAS.



Approximate Size
Width 648.0
Length 489.6
Unit Scale
XZ Plane 144.0
Depth 144.0
Load 10.8
○ Column Type 1
● Column Type 2
Create Column

Sphere
Radius 200
Apply to Top...
Ignore Height ☐
Ignore Width ☐
Ignore Length ☐

Figure 3: *Images 1 through 4 illustrate base unit 1 being morphed in SAFAS.*

6 Initial Results and Discussion

As a formative evaluation of our engineering process and eLearning tool, we sought out a qualitative review (walkthrough) by a professor. We are seeking to understand how our considerations play out to provide the cognitive scaffolding to acquire structural, procedural and behavioral knowledge. The following are the results organized by module:

Explanatory Resources

1. *Structure and Location Knowledge:* Possibility of the creation of various configurations using different base modules and analysis of each form based on the assembly of simple platonic solids help with better visualization of each form.

2. *Procedural Knowledge:* Several computer animated case studies of building structures help students better understand the construction process of the spatial structure systems.

3. *Behavioral Knowledge:* Learning about the historical development of spatial structures as related to the understanding of their design and construction in addition to their advantages and disadvantages are important and necessary aspects of the developed learning materials. They help student gain a better understanding of this structural system.

Interactive Resources

1. *Structure and Location Knowledge*:

    (a) It is easy to distinguish the differences between the various configurations and select the desired form. The color-coded nodes and members help users better comprehend the complexity of the structural forms.

    (b) The placement of the supports is simple and intuitive; however, it may require an easier way of defining the type and the height.

2. *Behavioral Knowledge*:

    (a) Morphing the various configurations based on selection of different top and bottom layer nodes using a sphere of influence concept is simple enough to be understood by the novices. In addition, other methods for defining the affected nodes should be available and the current linear interpolation of the selected nodes' movements needs to be extended. This way, the user will have more flexibility to define his/her desired geometry.

    (b) Selection of the member sizes at the initial stage and following iterations using the SAP computational engine needs further development.

    (c) Application of the applied loads is simple enough to be used by the experts. However, this needs improvement for the novice users by providing background information within the Explanatory Resources and linking it to this step of the task. Based on his/her need, the novice user can gain background information on loading before continuing with the task at hand.

    (d) Exporting the model to the structural analysis program (SAP) is easy to execute and the user may not need to directly be involved in this process.

    (e) Post-processing the results of the structural analysis using the color-coded members and nodes to show the deformations and stresses can be easily understood by the experts. However, other techniques may need to be tested for the novice users for better comprehension.

It is clear that this is a work in progress and both sub-modules require further development and integration before they can be used by students.

Future Improvements

1. *Architectural elements:* we intend to add a scene graph branch for the integration of architectural design elements and models. These elements such as walls, windows, doors structural engineering models are separate from each other in that only the structural model will be active (subjected to loads and deformations). However, we are interested in linking the architectural model and the structural model at different points in the design process- as the user modifies and/or morphs his/her ideas.
2. *Import-Export:* we intend to document and simplify data pathways to work with commercial programs being used by professional engineers; for example, loading models from AutoCAD and saving models for the SAP2000 structural analysis software.
3. *AEC Standards Support:* we will leverage standards and best practices from the Building Information Modeling (BIM) domain; for example, following NIST's work with IFC and the CIS/2 standard [Ref 2010]. We can use these databases to create integrated, accessible reports and parts lists.
4. *Hyperlinked resources:* as we continue to improve the interface of our form and structure design tool, we will curate and link in our own explanatory resources as well as those on the World Wide Web. This coupling will substantially increase the explanatory power of the interactive tool.
5. *Model checker and Recommender system:* we would like to explore how ontologies and expert systems may be integrated into the learning and design process; for example the expression of structural relationships could capture constraints enough to provide guidance on: spatial structure configurations for a specific application, module size and required depth for a particular span and loading condition, and initial sizing of the structural members.

Within the architectural design process, architects are generally responsible for defining the form of a project. Clearly however, understanding the relationship between the form and structural performance is crucial for feasibility, safety, and cost-effectiveness. By providing an interactive link between form and structure concerns, students (and practitioners) can compare the deformations and stresses of their designs under a range of environmental conditions and so help students understand the impact of their design choices. Since the creation and modification of the spatial structures is simple and intuitive, it is expected that users of many levels of technical knowledge can learn something from the system.

7 Future Work

In the future, we would like to extend the evaluation of our method with a formal user study to measure how much the developed system can improve learning. Even though the initial qualitative review of our system was satisfactory, it has been evaluated by domain-experts based on the current state of the system development, which is not enough to validate the effectiveness of SAFAS as an educational tool. In order to do that, upon further development of both Explanatory and Interactive resources, we plan to use the system in future iterations of the design studio and lecture courses in the Architecture program of our university in addition to two other schools.

In the current stage of our project, we are focusing on the desktop version of the tool. In the future, we intend to use this tool with other hardware configurations (e.g.: the CAVE [Cruz-Neira et al. 1992]), and evaluate the benefits of higher levels of immersion for learning systems in the domain of architecture. As shown by [Schuchardt and Bowman 2007] and [Wickens 1992], various types of applications can benefit from immersion, including learning tools. However, the challenge remains the practicality of using such tools and how to incorporate them as supplementary learning materials in a class. We speculate that recent advances in the 3DUI area and the use of off-the-shelf devices combined with Web3D technologies may help making the use of immersive virtual environment in classrooms practical.

Our task will also include the evaluation of interaction techniques designed for this specific domain. As mentioned before, the domain specific design aims at increasing the usefulness of the application by providing tools and interaction techniques that allow users to perform tasks specific to that virtual environment. We also need to make sure these techniques can be used in the desktop and in an immersive environment.

Finally, we would like to evaluate different visualization techniques for the representation of loads, stresses, forces and the results of the simulation. As shown in the Case Study section, we already have the initial design of how to store and display such information. However, we would like to perform a formal evaluation of the visualization techniques we are using to assess their cognitive value.

In this case study, we have shown how mapping expert requirements through cognitive considerations and psychology research results can benefit the usability engineering of an interactive learning system. However, we acknowledge that the cognitive-psychology expertise or inter-disciplinary resources required for this is not available to all software teams. Therefore, it is important for future research to derive actionable guidelines and checklists for the usability engineering of learning software. Indeed, such design guidelines are needed for Web3D as well.

Acknowledgements

The study presented here was supported by the National Science Foundation under grant No. TUES- 0817106. This support is gratefully acknowledged. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the view of the National Science Foundation.

References

BIEDERMAN, I. 1987. Recognition-by-components: A theory of human image understanding. *Psychological Review 94*, 2, 115–147.

CAMPBELL, B., COLLINS, P., HADAWAY, H., HEDLEY, N., AND STOERMER, M. 2002. Web3d in ocean science learning environments: virtual big beef creek. In *Web3D '02: Proceedings of the seventh international conference on 3D Web technology*, ACM, New York, NY, USA, 85–91.

CHEN, J., AND BOWMAN, D. A. 2006. Effectiveness of cloning techniques for architectural virtual environments. In *VR '06: Proceedings of the IEEE conference on Virtual Reality*, IEEE Computer Society, Washington, DC, USA, 103–110.

CHEN, J., AND BOWMAN, D. A. 2009. Domain-specific design of 3d interaction techniques: An approach for designing useful virtual environment applications. *Presence: Teleoperators and Virtual Environments 18*, 5, 370–386.

CHITTARO, L., AND RANON, R. 2007. Web3d technologies in learning, education and training: Motivations, issues, opportunities. *Computers & Education 49*, 1, 3–18.

CRUZ-NEIRA, C., SANDIN, D. J., DEFANTI, T. A., KENYON, R. V., AND HART, J. C. 1992. The cave: audio visual experience automatic virtual environment. *Commun. ACM 35*, 6, 64–72.

HIX, D., AND GABBARD, J. 2002. Usability engineering of virtual environments. In *Handbook of virtual environments: Design, implementation and applications*, K. Stanney, Ed. Lawrence Erlbaum Associates, Mahwah, NJ, 681 699.

HOLLANDS, J., AND WICKENS, C. 1999. *Engineering psychology and human performance*. Prentice Hall, Upper Saddle River, NJ.

IRANI, P., AND WARE, C. 2000. Diagrams based on structural object perception. In *AVI '00: Proceedings of the working conference on Advanced visual interfaces*, ACM, New York, NY, USA, 61–67.

LIAROKAPIS, F., MOURKOUSSIS, N., WHITE, M., DARCY, J., SIFNIOTIS, M., PETRIDIS, P., BASU, A., AND LISTER, P. 2004. Web3d and augmented reality to support engineering education. *World Transactions on Engineering and Technology Education 3*, 1, 11–14.

MCCLEAN, P., SAINI-EIDUKAT, B., SCHWERT, D., SLATOR, B., AND WHITE, A. 2001. Virtual worlds in large enrollment biology and geology classes significantly improve authentic learning. In *12th International Conference on College Teaching and Learning (ICCTL-01).*, 111–118.

MUNRO, A., BREAUX, R., PATREY, J., AND SHELDON, B. 2002. Cognitive aspects of virtual environments design. In *Handbook of virtual environments: design, implementation, and applications.* Lawrence Erlbaum Associates, Mahwah, N.J.

NIST, 2010. Product data standards for structural steel. http://cic.nist.gov/vrml/cis2.html, May 1.

POLYS, N. F., SHAPIRO, M., AND DUCA, K. 2007. Irve-serve: a visualization framework for spatially-registered time series data. In *Web3D '07: Proceedings of the twelfth international conference on 3D web technology*, ACM, New York, NY, USA, 137–145.

ROSSON, M. B., AND CARROLL, J. M. 2002. *Usability engineering: scenario-based development of human-computer interaction*. Morgan Kaufmann Publishers Inc.

SALZMAN, M. C., DEDE, C., LOFTIN, R. B., AND CHEN, J. 1999. A model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators and Virtual Environments 8*, 3, 293–316.

SCHUCHARDT, P., AND BOWMAN, D. A. 2007. The benefits of immersion for spatial understanding of complex underground cave systems. In *VRST '07: Proceedings of the 2007 ACM symposium on Virtual reality software and technology*, ACM, New York, NY, USA, 121–124.

VOGEL, E. K., WOODMAN, G. F., AND LUCK, S. J. 2001. Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance 27*, 1, 92–114.

WARE, C. 2000. *Information visualization: perception for design*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.

WICKENS, C. 1992. Virtual reality and education. In *IEEE International Conference on Systems, Man and Cybernetics*, 842–847.