

SAFAS: Unifying Form and Structure through Interactive 3D Simulation

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Abstract

There has been a significant gap between the tools used for the design of a building's architectural form and those that evaluate the structural physics of that form. Seeking to bring the perspectives of visual design and structural engineering closer together, we developed and evaluated a design tool for students and practitioners to explore the inter-relationships between the *form* and *structure* of long span structures. We have developed an interactive 3D design application for spatial structures that integrates with a web simulation service, enabling the iterative analytic comparison of designs by structural weight, force distribution, member deflection and stability. In this paper, we describe the design and development of this Structure And Form Analysis System (SAFAS) tool using the usability engineering methodology, presenting its evolution and evaluation through four semesters of use in undergraduate architecture classes. In this paper we present our summative results and lessons learned for the usability engineering of e-Learning systems, scientific visualization of structural dynamics, and user skill sets.

Introduction

The building industry has evolved with a division of labor that reflects two very different perspectives on the same coin. Architects, historically, are concerned with the form, perception and use of built spaces whereas structural engineers are concerned with the physics and forces at work in the spaces we build. There are, of course, rich and important relationships between these concerns of form and structure and these are naturally expressed in 3 Dimensions (3D). In this paper, we present the results of our work in the usability engineering of an interactive 3D design and analysis tool for long span, space frame structures.

The Structure And Form Analysis System (SAFAS) project is ultimately intended as pedagogical tool for undergraduate architecture education; however, its functionality is unique and significant enough for use by practitioners as well. The project is a collaboration between the Architecture, Education and Computer Science departments at Virginia Tech to develop and evaluate the use of simulation tools in design education. There are both explanatory and interactive resources for the structure and form curricula. The explanatory resources include an online website with extensive text, image, video and 3D resources on the origin, types and properties of space frame structures (Module 1). In this paper, we detail the evolution and design rationale behind the online interactive courseware, SAFAS Module 2 (see also: Bacim et al., 2010; Setareh et al., 2012; Polys et al., 2013; Jones et al., 2014).

We consider design as an iterative process of *generation* and *reduction*: designers generate multiple solutions to a problem and then reduce those alternatives to the most

feasible or functional or aesthetic solution. There may be several criteria or requirements for designers to balance in their solution. As both engineers and artists recognize, there is both science and art in tradeoff analysis: multiple local minima or maxima may exist and these are not likely the same as the global minima or maxima. In the exploration of the parameter space over several design iterations, a solution may converge slowly or it may appear unexpectedly in a flash of intuition. In order to reduce the design time to solution, we believe that digital design tools and simulation engines should be well integrated in order to tighten the design cycle between generation and reduction. This integration requires both a system with a flexible design interface that can execute simulations and a powerful analysis interface to explore and portray results.

SAFAS is such a system; it consists of a client and a server application that work together to support the convergence of architectural design and structural engineering activities. The client is a 3D space frame designer that includes several menus and modes with which to create expressive and realistic long span structures. Direct manipulation tools allow users to interactively deform the structures into novel shapes. Users submit their models to a structural simulator server over the web and receive the results back for analysis and comparison with other designs. Through this iterative, experimental process, SAFAS supports online inquiry-based learning (Furtak et al., 2012).

SAFAS was developed over several years with deployments in three universities over four semesters. We used Scholar/Sakai as our common course management system to deliver six different online lab assignments. As the tool evolved, we collected extensive feedback from the students about the performance and usability of SAFAS. This feedback guided our user interface and software improvements and provided empirical data on undergraduate student outcomes. In this paper, we detail the iterative usability evolution of SAFAS, presenting specific results bearing on the visualization of force, load, and deformation of steel structural members in 3D. We conclude with a discussion of how complex (spatial) concepts can be more clearly conveyed with interactive 3D simulation tools and the potential for future e-Learning systems.

Background

Interactive 3D Courseware

Online courseware and virtual 'lab-based' activities are gaining widespread adoption in K-12 and higher education. Many architectures and software have been deployed as educational applications and content have moved from server-based to client-based to client/server based and now back again to server-based (web/cloud). There are strong budget and mission pressures in education and therefore premium value is given to content accessibility, portability, durability and interoperability. As technology platforms evolve at a rapid pace, practitioner communities still face the challenges of digital content management and publishing in a world with a 3-5 year hardware lifecycle. Cooperative development and adoption of standards through International bodies such as

Web3D, ISO, W3C and IMS provides one essential strategy to balance innovation with sustainability.

Interactive 3D pedagogical content in domains from cell biology (Saini-Eidukat, 1999; White, 1999), astronomy and physics (Chakaveh et al., 1999) chemistry (Abdul-Kader, 2008) and optics (Thomas et al., 2008) has been demonstrated and evaluated with generally positive results. The successful cases are all a result of close collaboration between the teachers and software developers. Formal materials such as conceptual inventories, standards of learning, and rubrics all come from the teacher's expertise and the system is built to meet those requirements. However, there is an additional complication in the usability engineering of e-Learning systems - the teacher is not the end user (Bacim et al., 2010). We developed SAFAS through several rounds of both structured and open-ended student and teacher feedback.

The SAFAS client is a cross-platform *3D design and review application*; it provides expressive tools for creativity, and supports an industrial-strength structural simulation engine to evaluate the forces and deformations in the structure. The original Structure Analysis Program (SAP) was developed at Berkeley in the 1970s as a general-purpose Finite Element Analysis software. Its older open-source version (SAP-IV) was written in FORTAN and it is now offered as commercial software by CSI-Berkeley (SAP-2000). Being built for engineers, both present a steep learning curve. Our SAFAS server exposes both SAP simulation engines through a web service, providing a queue manager that processes SAFAS client simulation requests.

Virtual Environments for Structural Engineering Education

The use of Virtual Reality technology has been developed and evaluated for teaching structural concepts as related to the performance of typical steel structures subjected to seismic excitations (Setareh, Bowman, Kalita et al, 2005; Setareh, Bowman, and Kalita, 2005). Following up on those promising results, we decided to drive the development and impact of SAFAS by emphasizing the new requirements of Portability, Durability, and Interoperability:

Portability of interactive 3D content: the open-source Xj3D rendering library (Java, OpenGL) provides cross-platform client application to visualize models and structural simulation results from laptops to immersive displays.

Durability: 3D Models and lab scenarios need to be reproducible decades after their creation. Extensible 3D (X3D) is an open, royalty-free standard developed through the Web3D Consortium and ratified through the International Standards Organization (ISO).

Interoperability: X3D and VRML model import/export; Industry Foundation Classes (IFC) and CIMSteel Integration Standard (CIS/2) export through server simulation engine (CSI SAP 2000).

3D Modeling and Design

There is at least 30 years of history behind 3D computer graphics, content creation and interaction with 3D models. Indeed, numerous fields ranging from CAD/3D modeling to sketch-based modeling and interaction have tackled this problem of authoring solid geometry, meshes and textured photorealistic worlds. Our spatial structures are like a 3D mesh in one way: a network of linear members connected at nodes (vertices). However, there are some important differences: space frames are comprised of rigid-body members arranged in 3 layers (top, bottom and web), each of which may have different pattern of connectivity and physical properties (size and material) of members (edges). We adopted existing modeling metaphors, namely parameterized proxy 'deformer' geometry that allows users to manipulate and displace all nodes in a selection.

Perception in Scientific Visualization

In the early visualization literature, researchers evaluated and ranked visual mappings for different information types; Table 1 shows the pre-attentive ordering of visual markers per data type, as a result of meta analyses done by Mackinlay (1986) and Cleveland and McGill (1984). These rankings were focused on the legibility of a visual attribute as function of human visual perception. For example, color is very good for representing nominal/categorical variables, but very poor for representing quantitative variables.

Table 1

Pre-attentive Rankings of Visual Markers in the Information Visualization Literature

Data Type	Nominal / Categorical	Ordinal	Quantitative
Most pre-attentive	position	position	position
	color	density	length
	texture	color	angle / slope
	connection	texture	area
	containment	connection	volume
Graphical Representation	density	containment	color / density
	shape	length	
	length	angle	
	angle	slope	
	slope	area	
Least pre-attentive	area	volume	
	volume		
	(Mackinlay, 1986)	(Mackinlay, 1986)	(Cleveland & McGill, 1980)

While ability to extract a specific value (search) and pre-attentively order it along a dimension (comparison) is crucial for SAFAS users, we are also interested in the next higher level of abstraction – pattern recognition – at local and global scales. For scientific visualizations like scalar quantities over a regular structural network, this means portraying the distribution of these values throughout the network. In this way, SAFAS enabled us to probe the value of several glyph representations and examine how their

combinations of visual properties can support users' recognition of patterns in the distribution of forces.

SAFAS Design and Development

To build a usable 3D design tool for space frame structures, we adopted the Usability Engineering methodology (Rosson & Carroll, 2002). Usability Engineering refers to the process of setting operational definitions of user performance, executing a task analysis and then iteratively prototyping and evaluating the user interface features to meet those requirements. In this section we report the results of this design and development process for the Structure and Form Analysis System (SAFAS), a cross-platform, open-source, Web3D tool for architecture and structural engineering.

Activity Design

SAFAS is a free, online educational tool for architecture students, engineering students, architects, engineers, and anyone interested in structural dynamics. The primary purpose of SAFAS is to help individuals better understand the relationships between structure and form by building spatial structures, subjecting them to environmental loading conditions and observing the results. There are two principal activities supported as: Structural Design Mode and Structural Analysis Mode.

Models can be built, saved, loaded and exported for virtual reality walk-through and web publication. Most importantly for the iterative exploration of 'authentic' structures, models can be submitted online to a structural simulation engine, which computes the deformations and internal forces based on the structural configuration, properties and the applied loads and returns these values to the client for visualization and analysis. Users' models are managed through SAFAS and submitted to the CSI SAP-2000 simulation engine running on the same server. The simulation results can then be visualized on the client where further revisions can be made, submission and comparison with other designs.

Structural Design Mode

Information Design

When users create a new building design, a dialogue window opens with a menu of established base unit types and a screen image with text boxes in it, locating each parameter in the context of the structure (see Figure 1). The eleven fundamental types of space frame units fall into four families: Rectangular Grids, Diagonal Grids, Rectangular/ Diagonal Grids, and Three-way Grids. These 3D base units, which repeat in two dimensions to create the space frame, are displayed at left. The set of unit types covers the base configurations available in industry practice today. Users can specify the dimensions of the structure, the number of units in the length and width dimensions, the depth dimension, the height, the dead load and the snow load (in pounds per square

foot) and choose among a set of column types (Post, Tree, Pyramid) and their distribution (edge, corner) as well as settings (blank, trees, and a 3D Virginia Tech campus model).

All parts of the structure are referenced to a database of standard steel members with actual geometric properties and weights. Upon parameter selection, SAFAS generates the space frame, evaluates the base loads and sets the steel size of all each member in the top, web and bottom layer members. Users can change the size of selected members at any later time in Design Mode.

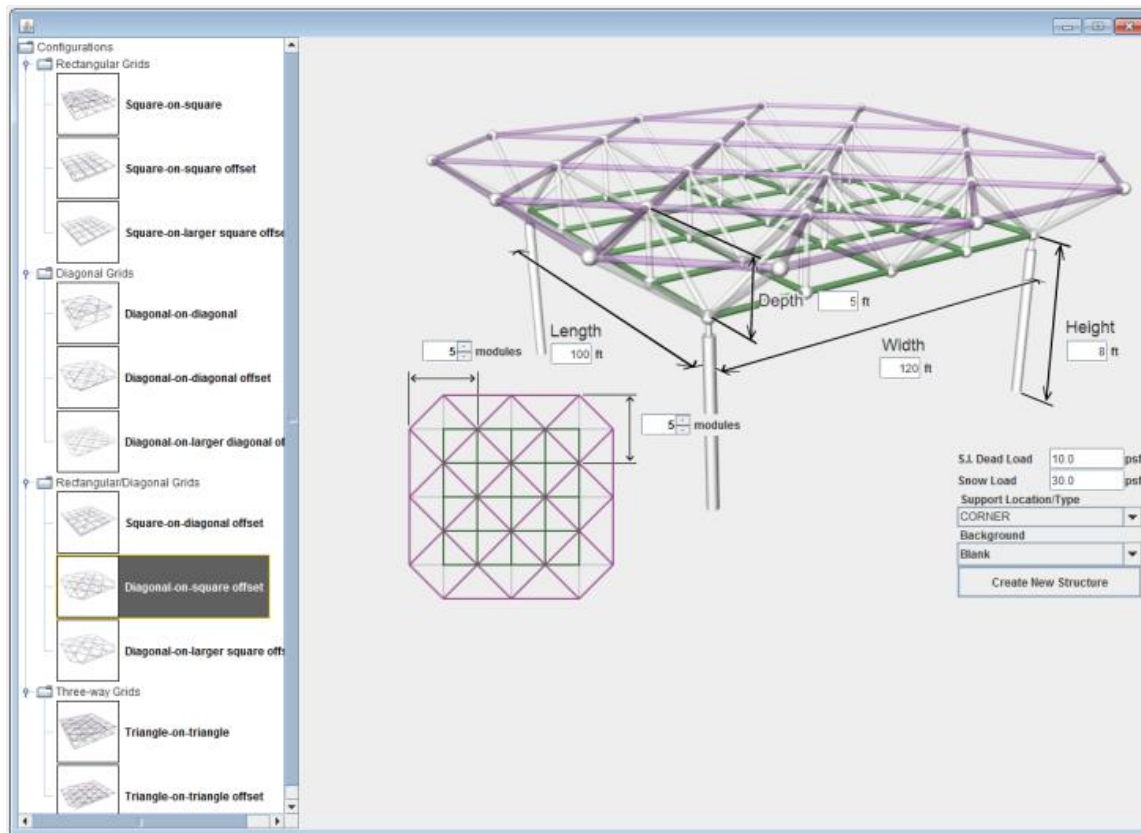


Figure 1. Specifying a space frame structure in SAFAS.

The generated structure is then displayed in the 3D panel with a categorical color coding by layer (green = bottom, white = web and purple = top layer). At the top of the SAFAS screen is a menu panel including six system and task-related pull-downs and then below them, shortcut buttons for common functions (with mouse-over tooltips) running from left to right. Down the right hand side of the SAFAS interface is a set of 2D control panels that are used to set parameters for Loading, Viewing, Comparing and Morphing. The color bar at the bottom of the screen indicates what mode the SAFAS is in: green for editing the structure (design mode), yellow for morphing the structure and red for inspecting the structure (analysis mode).

The newly created structure is shown in an interactive 3D window. The loads at each node in the structure can be rendered as arrow glyphs and/or with a color coding (white to red). As users mouse-over the nodes and members of the 3D structure, the elements highlight to yellow showing they are selectable. For members, their size, area and length is shown in the upper right in a Heads-Up-Display (HUD); for nodes, the x, y and z position as well as load are displayed. The 3D Axes included in the lower left of the HUD shows the user's orientation relative to the model (see Figure 2).

Interaction Design

To navigate in SAFAS, users orbit the structure by clicking and dragging the right mouse button. The position of the virtual camera is constrained to stay above ground-level. The mouse scroll-wheel zooms in and out of the scene toward the current cursor position (target-based zoom). Users can also use a pull-down menu in the right 'View Control' panel to jump to specific viewpoints.

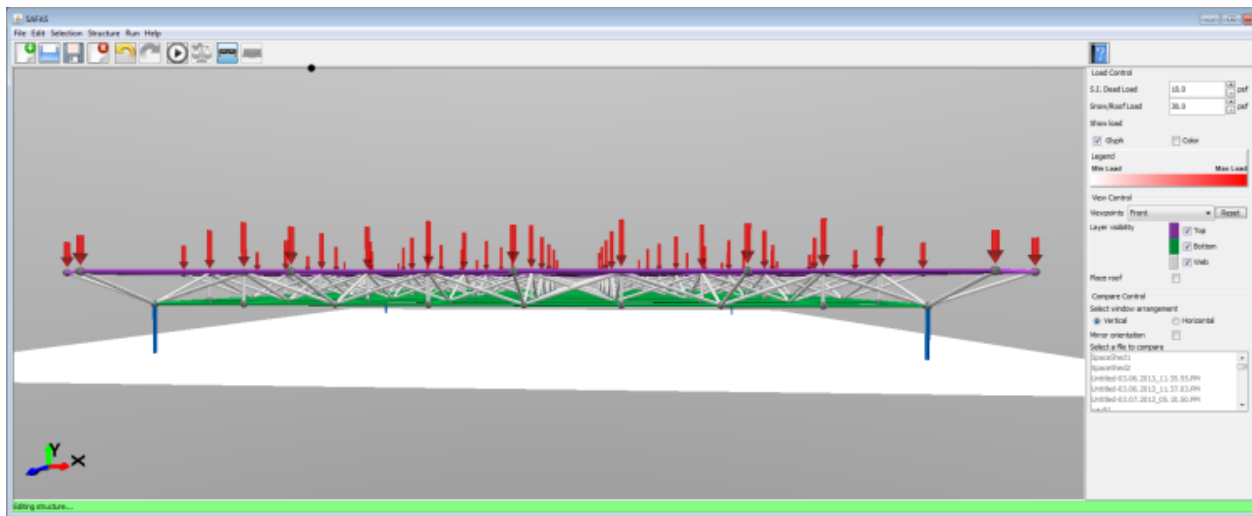


Figure 2. A newly-created structure showing node load as a glyphs.

The design interactions for the creation of architectural forms in SAFAS are driven by a rich set of functions. In the content-sensitive Morph Control panel at right, users can specify the properties of the deformer geometry that is used to shape the structure. The deformer geometry (a sphere or a cylinder) may be sized by radius and, in the case of the cylinder, aligned to any angle in the horizontal plane. We integrated a useful student suggestion for a shortcut button to size the deformer geometry to be the maximum dimension of the current structure.

A morph action can also be customized with regards to the effect of the deformation of selected nodes within the proxy geometry. Through a pull-down menu, users can choose from a set of functions that determine the deformer's effect from the center of the selection to its radius; for example, the displacement of the nodes can follow a

smooth bell curve, a linear function, an elliptic or a uniform function. Through a 2D graph panel at bottom right, users can further customize the profile of the effect function by directly manipulating control points on the curve (see Figure 3).

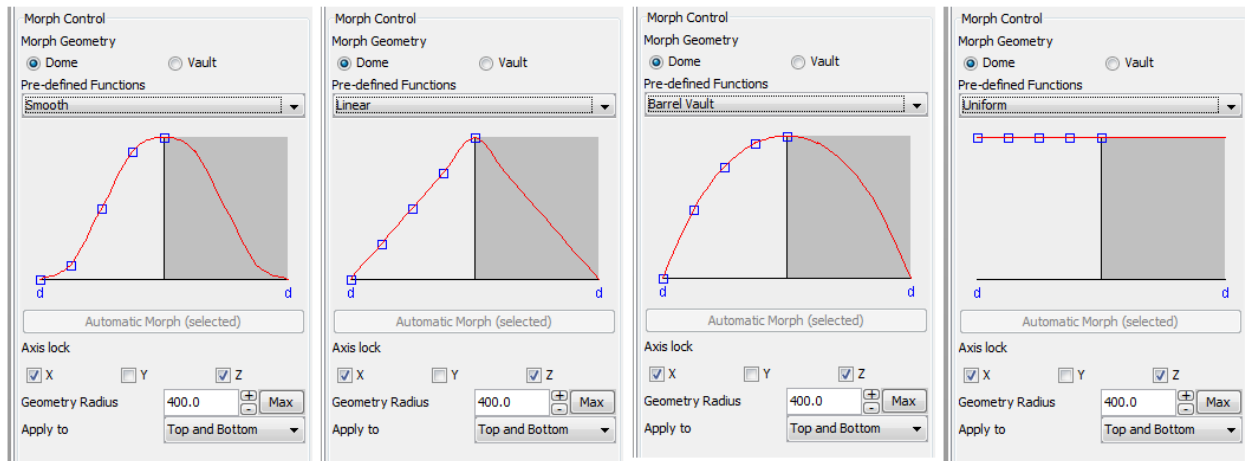


Figure 3. Close up of curve functions driving the SAFAS soft-selection design deformers.

The shape deformation of the structural network can be further specified to effect by layer or be independently constrained along any of the three axes. The selection of nodes within the deformer geometry is color coded to show the degree of effect a morph action will have on that node. Ultimately, a morph action can be executed with a direct manipulation (mouse click and drag) or by entering in displacement numbers (in inches) along any of three axes. The result is a built shape or form that is a structure specifying real steel members and under specific loading conditions (see Figure 4).

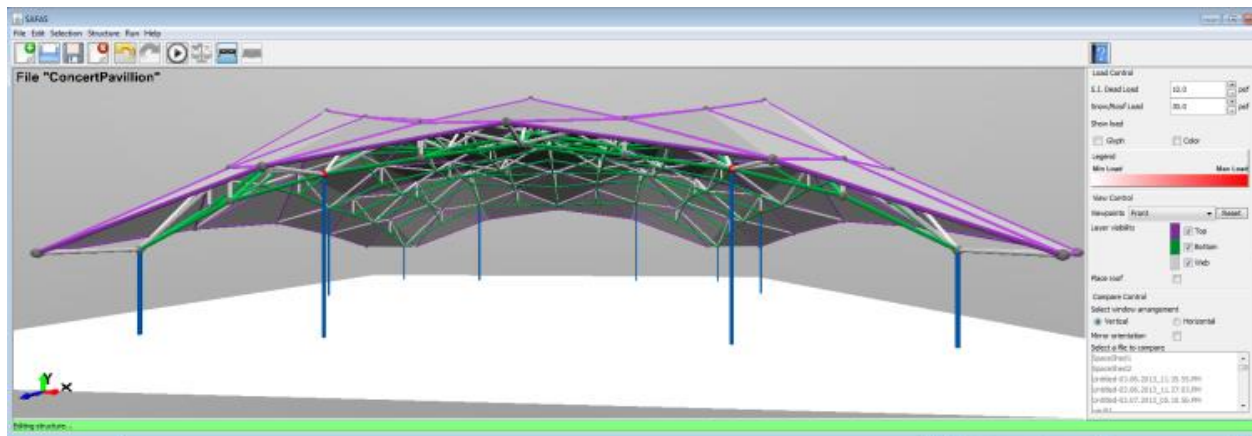


Figure 4. Example structural form designed in SAFAS.

To submit a structure design to the SAFAS server for simulation, users can use the 'Run' menu or the shortcut button at top. Users can specify their own name for the design, which is saved and submitted to the SAFAS server. An alert box shows the sub-

mission, processing and reception stages of communication with the server.

Structural Analysis Mode

Information Design.

After a structure has been evaluated on the server and the results returned to the design client, users have a number of options for visualization and analysis of the simulation results. In the 3D window, users can query specific nodes and members to view numeric results with a mouse-over. By mousing-over a node, the upper right of the HUD shows a numeric readout of their x, y and z position as well as the directional load; mousing-over a member shows its forces numerically in the HUD.

The challenges of visualizing continuous data on a spatially-discrete network are significant. For example, there are several values of interest to represent in the context of occlusion and repetition in the structure of the network itself. In order to understand the relationship between structure and form, users must be able to find 'hot spots' as well as recognize patterns in the force distribution. To visually communicate the structural properties of a space frame form, we devised three visualization mappings of data values to visual values and one time series mapping (displacement animation) described below.

Table 2

Visual Mappings Used to Portray Force in a SAFAS Structural Network

Visual Mapping	Description	Categorical variable (+/-)	Quantitative variable
Color	Members' material properties are changed to show a diverging color scale going through white at 0 where tension is blue and compression is red; the member keeps its realistic size.	Hue	Luminance
Cone glyph	The member keeps its realistic size. Two yellow cones are shown at each member's midpoint; the cone's orientation shows direction of force, cone radius shows magnitude of force;	Orientation	Size
Cylinder glyph	A cylinder at each member's location is colored red or blue for direction to type of force and the cylinder's radius shows magnitude of force	Hue	Size

The distribution of tensile (+) and compressive (-) forces in the structural members can be portrayed through any of the three available visualization mappings. Table 2 summarizes the visual mappings used in the SAFAS structural analysis mode; Figure 5 shows an example of each. Checkboxes in the View Control panel at right enable the 'Highlight Max' and 'Highlight Min' buttons, which provide a quick assessment of extreme forces in the structure (with the active visualization mapping).

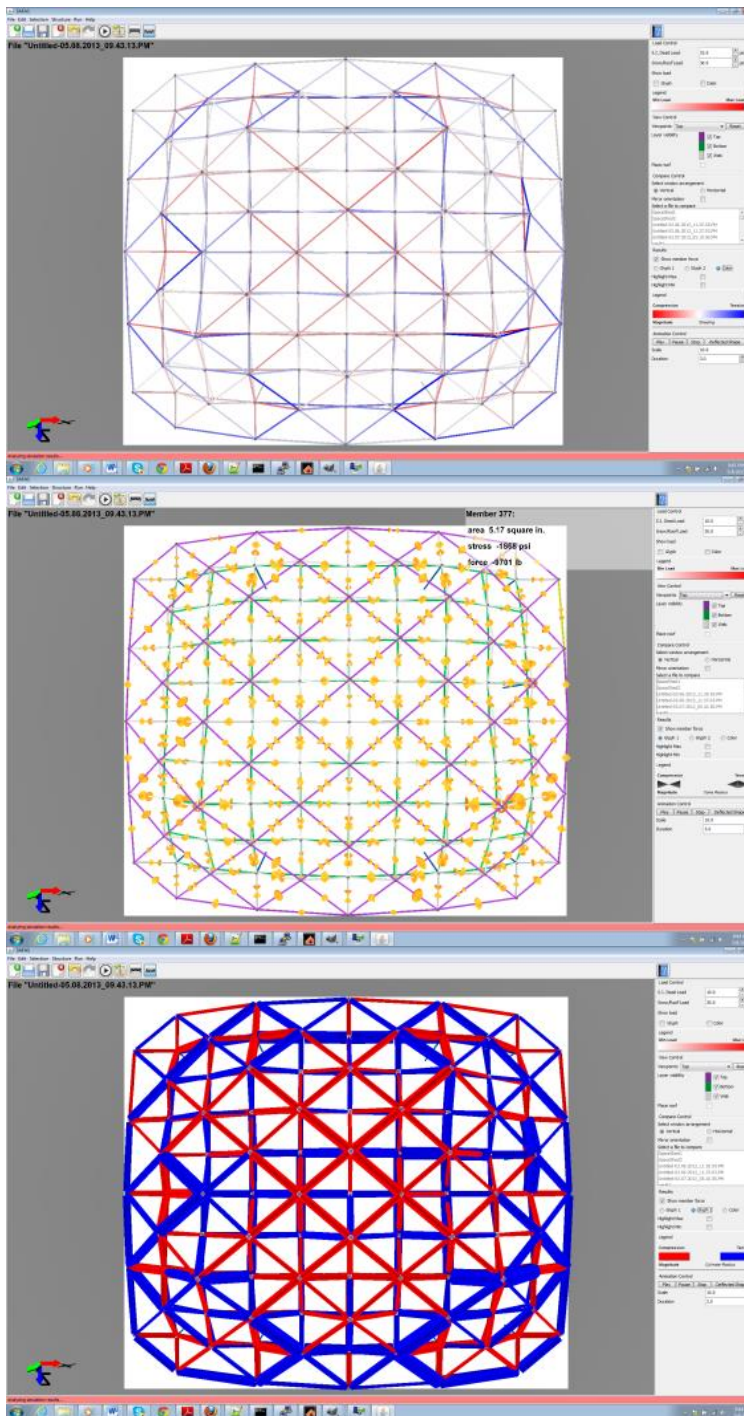


Figure 5. Visual Mappings of forces in discrete members.

There are a variety of color maps discussed in the literature and deployed in scientific visualization, depending on the distribution of data values to be mapped. Considering that force is a range on both sides of zero, we can say we need to represent the quantity of force magnitude in two different categories (positive or negative). We followed Mo-

reland (2009), adopting a linear diverging scale from blue to red for our first mapping. In the second mapping, we also preserve the structural members' actual size, but add an additional shape whose orientation and size portray the force in the member (cone glyph). The third mapping replaces the members' geometry with either a solid red or solid blue cylinder; where the size of the cylinder is proportional to the force magnitude.

Interaction Design

The calculations done by SAP on the SAFAS server return the internal forces in the structural members as well as the physical displacement of the nodes. The SAFAS client can display this information by mouse-over of a node or a member (numbers appear in the HUD) or with a 3D animation. The Animation Control panel at bottom right provides buttons to Play, Pause or Stop the animation as well as to snap to the final loaded shape. Users can enter their own values to uniformly scale the displacement animation or to adjust the playback speed of the animation.

In the design of an architectural form and the optimization of a structure's integrity, several versions of the model may be built. SAFAS allows for the side-by-side comparison of two different structures and their simulation results. In Compare Mode, users can select any prior models to load in an adjacent window (see Figure 6). 2D user interface elements in the Compare Control at right allow the windows to be tiled horizontally or vertically as well as for navigation to be synchronized between windows (mirror orientation).

SAFAS Implementation

SAFAS 3D design client is built on Java, Extensible 3D (X3D) and OpenGL. NetBeans and SVN was used as the project development platform. We exposed the Structure Analysis Program (SAP) simulator programs through a custom-built web-service and queue manager, which tracks users and their job submissions on a Windows Apache server. Structures with thousands of elements are easily evaluated and returned in a few seconds. Online video tutorials were developed showing each of the features and processes of SAFAS necessary for the assignments. The software engineering aspects of our Web3D User Interface can be found in Polys et al. (2013).

Using our SAFAS 3D design application (Java client) and the online resources, students were asked to construct building structures with specific properties and to critically review the structural behavior. Each semester, we released a new version of the tool for use by the students. The development of the graphical user interface was a main focus as we iteratively improved the features based on the feedback of students from the online assignment questionnaire.

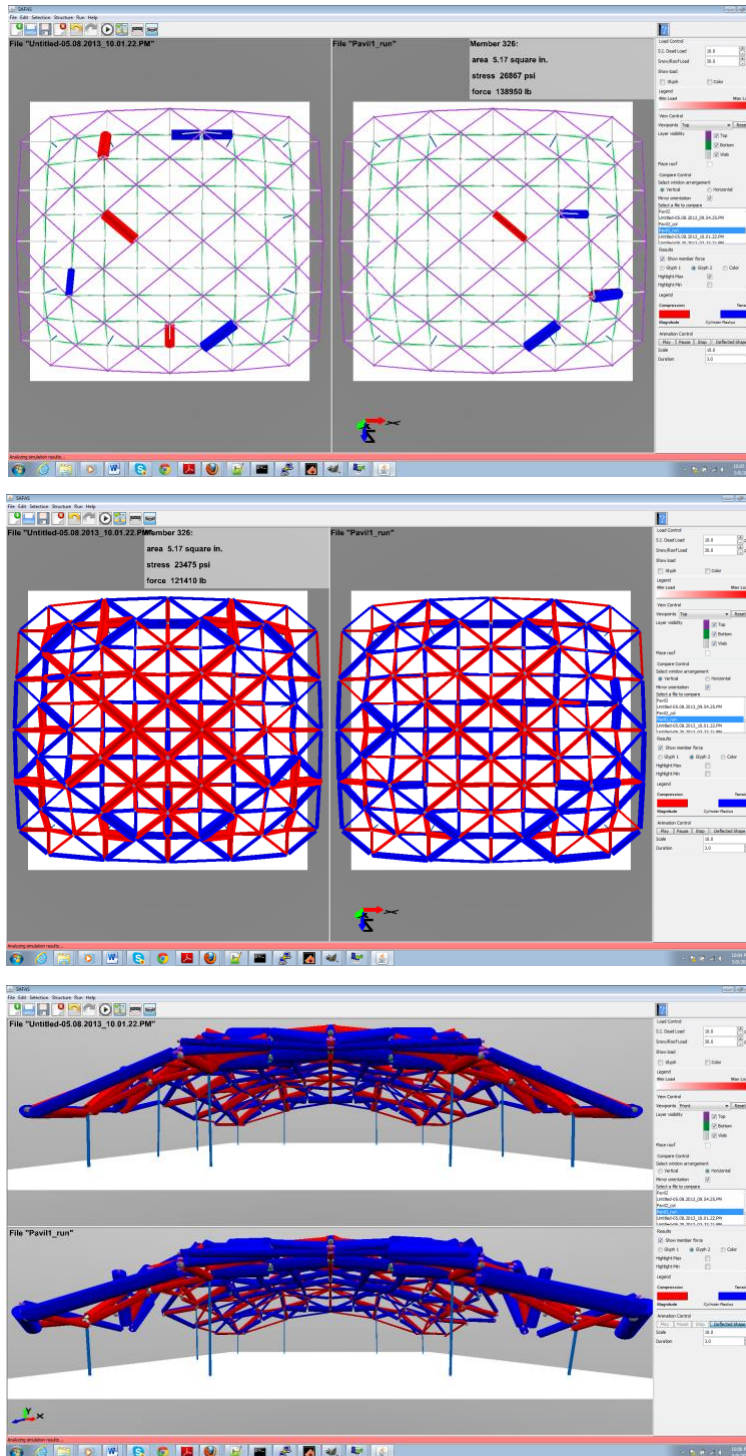


Figure 6. Comparing the two structures in SAFAS Analysis Mode with the Cylinder glyph after adding two columns to keep the structure from collapsing; the top and middle plan views show the new structure design at left, original at right; the bottom screenshot shows the deflected shapes with the new design at top of 'landscape' compare mode.

The server-side system (web simulation service, queuing manager and file management) was integrated and tested with the open-source SAP IV as well as the commercial SAP 2000 structural simulator software. The design client was compiled and packaged for several platforms so that students could run it on their laptops or home machines. Finally, we implemented stereo rendering for the SAFAS 3D component and installed a version on the large passive stereo (circular polarized) projection wall in the Virginia Tech Center for Advanced Visual Media (CAVM) lab (see Figure 7).

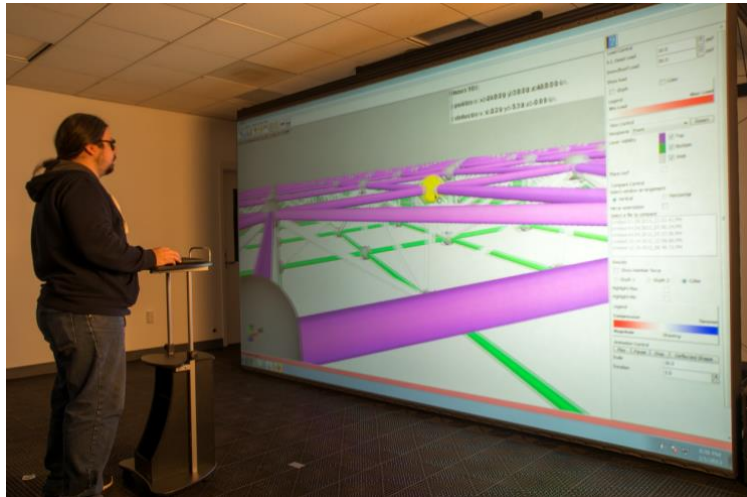


Figure 7. SAFAS designer on our Stereo wall.

The online assignments were designed so that, through their completion, students would learn the key structural concepts for their class level (see Table 3). To better understand the effects of form on structural behavior, the assignments required students to design both flat and barrel vault double-layer grid spatial structures. Typically, the procedure was to: log into the courseware website (Scholar/Sakai) and begin an assignment. Assignments were not timed and students could stop and resume any number of times before the deadline.

Table 3

Assignment topics used in SAFAS evaluation

Assignment	Key Structural Concept
1	the effects of the number of supports on structural behavior
2	the effects of support number and location on structural behavior
3	the effects of span-to-depth ratio on structural behavior
4	the effects of overhang length on structural behavior
5	the effects of different support types on structural behavior
6	the effects of different grid configurations on structural behavior

The assignments consisted of a set of instructions such as *'build a structure with the following dimensions and properties ...'*, which students built with the SAFAS designer. Once students had built and analyzed the structure, there were a series of tables/ forms in the Scholar assignment to fill out; for example: questions about the various forces (min/max) and their distributions. Students had to extract the values from the SAFAS interface and enter them into the online assignment forms for grading. Each assignment included a section with reflective questions about the tool, including its features and ease of use (see next section). Each assignment took on average about 1.5 – 2.0 hours to complete and students were offered extra credit for their participation.

SAFAS Evaluation & Evolution

Over the course of this project, we iterated the SAFAS development through four semesters of formative evaluations. Each semester, students downloaded the client and installed it on their personal computer, completing the assignments and feedback questionnaires through Scholar. Our iterative tool development relied on structured and open-ended feedback questions from the users, yielding actionable results throughout the evolution of SAFAS.

Versions 1 and 2

The first two semesters were primarily spent developing the SAFAS tool's functionality, its user interface and the first 3 assignments. In Fall 2010 and Spring 2011, N = 11 and N = 35 respectively. At this early stage of development, the open-ended questions were a potent source from which to gather feature suggestions and improvements from the students. A majority of these suggestions were integrated into subsequent versions of the tool. After consideration from the team, several important features as varied as pull-down menus to automatic morphing dialogue parameters to 3D navigation and coupled views between compare windows, were implemented as the direct result of this user feedback.

The structured questions asked students to respond with a subjective rating (Likert scale: 1 (*strongly disagree*), 2 (*disagree*), 3 (*neutral*), 4 (*agree*), and 5 (*strongly agree*)). These types of questions were designed to assess students' perceptions of the various functions of the SAFAS, as well as to assess students' beliefs about their abilities and motivation related to the SAFAS. They also helped us in identifying problem spots and prioritizing our work items. After reviewing the Fall 2011 results (reported in Setareh, Bacim, et al., 2012), we were confident we had a reasonable framework and tool that could be further developed to meet our research and pedagogical goals.

Version 3

We continued to develop the SAFAS as well as the protocols to assess it with (i.e. Assignments 1 through 3). In the Fall semester of 2011, we included students in another undergraduate architecture course at a different university for N = 78. In this iteration,

we focus on assessing the relationships between users' skills, their tasks, and how the different representations presented in the 3D tool support the conceptualization of structural dynamics.

Each student completed the Purdue Spatial Visualization test (Guay, 1976; Bodner & Guay, 1997) at the beginning of the semester, delivered through our online Scholar (Sakai) system. We conducted several statistical analyses on the results of the spatial visualization test and student scores. Over all three assignments (1-3), there was a strongly significant correlation between their spatial visualization skill and their final scores (Pearson $R = .341$; $p = .002$). The student scores on the Purdue visualization test were positively correlated with their performance on specific assignments, notably, Assignment 1 and Assignment 2. On Assignment 1 (the effects of the *number* of supports on structural behavior), the correlation with Spatial Visualization was $.304$ with a $p = .007$ ($n=78$). On Assignment 2 (the effects of support *number and location* on structural behavior), the correlation was $R = .275$ with $p = .016$ and $n=76$.

At the beginning of Assignment 1, we had a set of ten questions that explicitly asked users to find the minimum and maximum loads on a structure with each of two visualization mapping (color and glyph). In Structural Design Mode, users can select to see the environmental load magnitude on nodes as either a color map (white to red) or as a vertical arrow's length (e.g. Figure 3). Users were asked to do this for both an edge-supported structure and a corner-supported structure. After the four questions regarding the load in each structure, users were asked "*After trying the "Glyph" and "Color" Visualization options, which one helps you better understand the properties of the structure?"*

Examining the responses of users by their spatial visualization score, we determined that a higher proportion of those on the lower end found the Color Map helpful. This difference was not significant by logistic fit or contingency analysis, but worth noting the trend that if we consider 'Low spatial visualizers' as scoring a 17 or below (out of 30), 55% of their choices were for the Color Map and 45% were for the Arrow Glyph. In contrast, 'High spatial visualizers' chose the Arrow Glyph 60% of the time.

At several points in each assignment, students were asked to record the visualization mapping that most helped them complete that analysis task (color map, cone glyph, or cylinder glyph). This allowed us to collect data regarding the perceived utility of the representations of force values in the structural members. Overall for three assignments (1-3) and semesters, the Cylinder glyph was strongly preferred to the Cone Glyph and Color for the visual mapping of tensile (+) versus compressive (-) forces. Out of the 684 total responses, 429 of those selected the Cylinder Glyph (62.7%), 175 selected the Color Map (25.8%), 80 selected the Cone Glyph (11.7%).

The Cylinder Glyph was clearly the most useful to students in completing their tasks overall. A one-way ANOVA showed this difference as significant both overall ($F = 56.90$; $p = .017$) and per assignment (for Assignment 1, $F = 34.58$ and $p = .028$; for Assignment 2, $F = 260.46$ and $p = .004$; for Assignment 3, $F = 76.91$ and $p = .0128$). Follow-up t-

tests of the Color versus Cone Glyph responses showed that although Color was preferred, overall the difference was not significant ($t = -4.037$ and $p = .060$). For Assignment 2 (the effects of support *number and location* on structural behavior), the difference between Color and Cone preference was significant ($t = -8.94$ and $p = .0198$) with users preferring the Color Map over the Cone.

Finally, we examined the role of spatial visualization skill on visual mapping preference. We did two post-hoc analyses, dividing the population into 'High' and 'Low' spatial visualizers. The cutoff value for these categories significantly affected these results, yet the threshold is rather small based on 30 questions. When we used a score of 18 and over (60%+) as the categorical cutoff value, there were 68 students in the High spatial visualization category and 10 in the Low category; when we made the cutoff at 20 and over (66.6%+), we had 55 in the High and 23 in the Low categories.

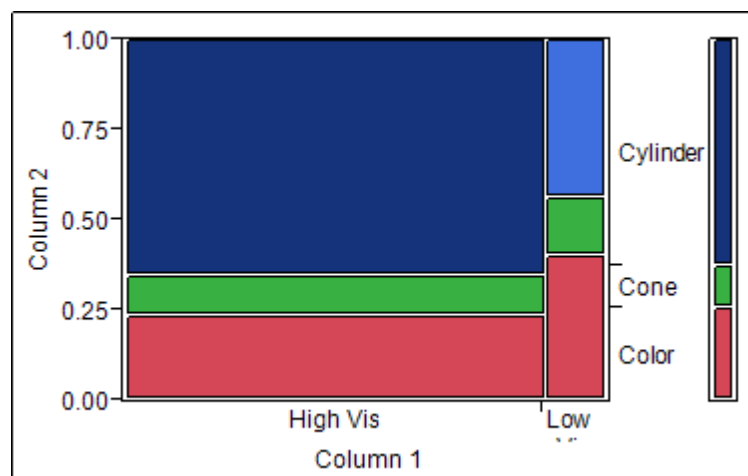


Figure 8. Color Preference per group: $p = .0004$.

A Contingency Analysis of user's preference for Color Map, Cone Glyph or Cylinder Glyph show that 'Low spatial visualizers' had a greater preference for the Color Map over Glyphs than 'High spatial visualizers' did. If we consider 'Low spatial visualizers' as scoring a 17 or below, we see a significant result overall: Pearson Chi-square = 15.474 and $p = .0004$ (see Figure 8). However, when we used 19 and below as the cutoff score for grouping, this difference was not significant (Pearson Chi-square = 4.558 and $p = .1024$ at $n = 684$).

Version 4

In the Spring semester of 2012, we developed and deployed the remaining assignments (4-6) and $N = 89$. Over all three of these assignments, again there was a strongly-significant correlation between good spatial visualization skill and good final scores ($R = .291$, $p = .007$, where $n = 86$). The students' scores on the Purdue visualization test were correlated with their performance on specific assignments, notably Assignment 4

and Assignment 6. On Assignment 4 (the effects of *overhang length* on structural behavior), the correlation with Spatial Visualization was $R = .428$, $p < .001$, $n = 86$. On Assignment 6 (the effects of *different grid configurations* on structural behavior), $R = .433$, $p < .001$, $n = 82$.

Across all of our evaluations of each Assignment 1-3 (SAFAS Version 3) and Assignments 4-6 (SAFAS Version 4), we asked students to rate their level of agreement with several "Ease of use" questions on a 5-point Likert scale. These subjective ratings showed that students generally agreed that the SAFAS features were easy to use, as evidenced by the fact that the mean values were about "4" for the ten specific questions presented (see Table 4).

The items with the highest ratings were those that related to the ease of placing the columns and the ease of understanding the definitions. All of the items were rated higher than "neutral" (on the "agree" side of the 5-point scale); however, the items with the lowest ratings were those that related to the ease of morphing the structural form, the ease of understanding the morphing options, and the ease of using the "Compare" window. The responses are generally on the positive side and even though Assignments 4, 5 and 6 were more challenging in demonstrating advanced concepts, we see a consistency across the SAFAS versions. We conclude that form and structure activities are well-supported overall by our interface features.

In the open-ended feedback section for each SAFAS Version 3 and Version 4, we asked: "What did you like least about using SAFAS?" We coded students' responses and compared Version 3 and Version 4. Some of the responses provided by students were similar across time points, but others were quite different. One difference was that students reported much less "crashing" or "freezing" of the SAFAS with Version 4 (2.2%) than with Version 3 (32.9%). Students also reported fewer "bugs" or "glitches" with Version 4 (11.0%) than with Version 3 (22.4%), as well as less trouble downloading the SAFAS Version 4 (1.1%) than Version 3 (7.9%).

These findings indicate that the modifications made by the SAFAS project team between Version 3 and 4 were successful in helping the SAFAS to run more robustly and efficiently. Other comments, however, showed that there was still room for improvement with about 10% to 15% of students reporting that the SAFAS runs slowly, was not user friendly, or had to be closed and re-started with a new structure if a mistake was made or if a re-analysis needed to be completed. Comments made by fewer than 7% of students with either version were that: SAFAS was hard to learn to use, the tutorials were boring, and that it was hard to select nodes or members. Additional details and data from an pedagogical perspective can be found in (Setareh, Bacim et al., 2012).

Discussion

Usability Engineering

When we first set out to build an accessible, free software system to tighten the architectural design loop in long span space frame structures, we faced several challenges. Our goal was to construct a user interface and system to support constructivist and experiential learning for architects. Therefore, it had to be an authentic tool that realized the actual complex physics involved in real structural frames. Second, it had to be an expressive design tool, capable of generating a wide variety of building forms. Third, it had to be usable by novices on a variety of client platforms – this includes ease of installation and execution and user interface.

Table 4

Students' Perceptions of the Ease of Use and the Helpfulness of the Features of Module 2

Questionnaire Items	Version 3 a: M (SD)	Version 4 b: M (SD)
Ease of use (1 – 5)		
1. It was easy for me to visualize the various configurations of spatial structures presented when I created a new model.	3.94 (0.90)	3.68 (0.81)
2. It was easy for me to note the differences between the various configurations.	3.86 (0.85)	3.73 (0.79)
3. Selecting members and assigning sizes to the structure was easy.	4.05 (0.99)	3.86 (1.07)
4. Morphing the structural form was easy.	3.45 (1.18)	3.28 (1.00)
5. It was easy to understand the different morphing options.	3.58 (1.09)	3.32 (1.03)
6. Placing columns was easy to do.	4.23 (1.04)	4.29 (0.94)
7. The “Compare” window was easy to use.	3.41 (1.37)	3.62 (1.13)
8. The following definitions were easy to understand: S. I. Dead Load; Snow/Roof Load; Glyph; Viewpoint; and Layer Visibility.	4.25 (0.86)	4.31 (0.81)
9. The definitions for structure, length, width, depth, height, module size, and number were understandable.	4.30 (0.96)	4.28 (0.87)
10. The SAFAS interface button icons (the shortcut menu buttons) were appropriate.	4.04 (0.99)	3.80 (0.91)
Helpfulness of features (1 – 5)		
1. The “Module 1 Topics” were helpful to me.	3.30 (1.01)	n/a
2. The materials in Module 1 helped me to note the differences between the various configurations.	3.48 (0.95)	n/a
3. The “Compare” window was useful to me to better understand differences between the performances of structures under loads.	3.91 (1.27)	3.75 (1.11)
4. The “color coding” of the structure helped me to understand the action of loads and distribution of forces within the structure.	4.03 (1.11)	4.08 (1.16)
5. The “Highlight Max” option helped me to understand structural behavior.	4.82 (0.62)	4.72 (0.74)
6. The “Help” topics were helpful to me.	2.94 (1.01)	2.94 (0.91)

Note: Response options included 1 (*strongly disagree*), 2 (*disagree*), 3 (*neutral*), 4 (*agree*), and 5 (*strongly agree*). ^a n = 78; ^b n = 89

Reflecting on the four (now five) iterations of the SAFAS, we can say that our original approach of adding an analytic ‘Cognitive Scaffolding’ step to the typical usability engineering process (Bacim et al., 2010) has guided our design and born fruit in a usable tool (i.e. Table 4). However, we can note a few qualifications that temper our original claims. First, despite frameworks for formal cognitive-task analysis and reductionism (Payne, 1986; Diaper, 1989; Schraagen et al., 2000), we still lack a complete picture of task and cognitive taxonomies across domains. Therefore, future research in applied HCI and 3DUI, especially e-Learning, should include deliberate efforts to identify and qualify the knowledge and cognitive operations required for a task in a given context.

The second observation worthy of noting is that for the SAFAS project, the Cognitive Scaffolding approach followed the law of diminishing returns. Specifically, it was the principle guide in developing the first and second versions of the software. However as the iterations progressed, the value of empirical evaluation increased. As the project progressed, many of the features were identified and validated by explicit user comments. In retrospect, this dynamic makes sense as the development effort shifted from the fundamental functionality to the usability of the client interface in supporting the specific activities and detailed work flows of the undergraduate assignments.

Scientific Visualization

The SAFAS project enabled us to explore some fundamental challenges of scientific visualization. Specifically, we evaluated the ranking of visual properties for the visualization of scalar values on (discrete) structural networks. We found that the Cylinder glyph (solid color hue for representing the categorical variable and size for representing quantitative variable) was the clear winner among the visual mappings tested. The results are generally in line with the information visualization literature where color is stronger than shape or angle for categorical data and area / volume is stronger than color for quantitative data. A caveat to this result is that for these tasks, there is no need to maintain the structure’s real size when comparing the sizes of the force within the member - we can sacrifice realism and use the virtual environment graphics to accentuate the properties of the structure (distribution of force magnitudes) for easy, pre-attentive comprehension.

In addition, we observed a trend that High and Low Visualizers preferred different visualization mappings. For the questions about load in Assignment 1, we saw Low spatial visualizers relying on the Color Map more than the Arrow glyph, whereas for High spatial visualizers, the Arrow Glyph was chosen the majority of the time. In the case of Assignments 1-3 and questions about force, this preference was significant with a larger proportion of Low spatial visualizers (vs. High spatial visualizers) choosing the Color Map. We believe this result makes sense that users without strong spatial visualization skill are compensating by focusing on cues in the scene that are not geometric, specifically the hue and luminance values of members.

The Role of Spatial Visualization Skill

The finding that student performance on several of these assignments depends on spatial visualization skills is not surprising in itself, but more interesting is to consider the reasons why this correlation was not uniform across assignments. The Purdue Spatial Visualization Test significantly correlated with performance on assignments 1, 2, 4, and 6 but not 3 and 5. These results suggest that tasks which require the processing of three dimensional locations and configuration information are particularly demanding for students with 'low' spatial skills. Conversely, we may conclude that the tasks involving the span-to-depth ratio and column categories do not significantly require the spatial visualization skill measured by the Purdue test.

These results confirm other studies in engineering education that found that spatial visualization skill is predictive of success in engineering undergraduates (Sorby et al., 2003; Branoff, 2009). This is good news, since spatial visualization skills can be learned through training and practice (Sorby et al., 2003; Sorby, 2009a; Sorby, 2009b). At Virginia Tech for example, incoming freshman to the College of Engineering take the test and those with a score of 17 and below are enrolled in a special (intervention) class that demonstrably improves their spatial visualization skill and their chances of success in the program. We consider this evidence as a strong mandate to work with more student populations, such as architecture students, on developing these skills early in their career. One set of activities is already available, although expensive (Sorby et al., 2003), and could be updated to use real interactive 3D models online instead of pre-packaged 2D animations from a CD-ROM.

Future Work

SAFAS provides a robust platform for designing space frame forms and evaluating their structural feasibility through simulation. The process of development has given us a richer understanding of the factors in building successful e-Learning systems and scientific visualizations. The SAFAS tool installer and curriculum will continue to be deployed for undergraduates at Virginia Tech. Interested parties should visit the website to request accounts for themselves and their class. We believe SAFAS can be a robust platform for further user studies on visual mappings, the benefits of immersion, and interactive techniques for shape deformation.

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