SMATS: Sketch-Based Modeling and Analysis of Truss Systems

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ABSTRACT: The present work intends to introduce a domain-specific sketch method for modeling and analysis of forms and structures of trusses concurrently. The main contribution of the research presented here is the development of a computer-assisted structural modeling tool where the structure can be sketched, subjected to loads, a structural analysis is performed, and the results can be observed. The Sketch-based Modeling and Analysis of Truss Systems (SMATS) allows the user to test what if scenarios in real-time by using simple sketches. To interpret the sketch and extract data for a structural analysis, SMATS uses a gesture recognition algorithm. The results are then brought back to the same environment for visualization in terms of color/thickness-code and animation. Moreover, the interactive environment of the user interface (UI) allows the user to manipulate the design and observe the outcome of the changes on the truss structural behavior. SMATS is developed for the particular use of architects, aiming to provide them a natural environment to present and appraise structural configurations of different truss systems by means of sketching. Iterative usage of the method will give architects, engineering perspective about the class of structures used here. The approach is intended to optimize the conceptual design of trusses by bridging architectural vision in creating forms, and engineering analysis. It also helps architects gain better understanding of the effect of variation in form on structural behavior of trusses. In addition to its application as a design tool, SMATS can be used as an effective educational tool. Architecture students have used it to learn about the fundamentals of structural engineering in building structures classes.

KEYWORDS: Sketch-based Modeling, Truss, Computer Aided Design (CAD), Design Integration, User Interface

INTRODUCTION

Sketching is an essential tool in the professional life of architect from the moment they start their education. Despite the advances in computer aided design (CAD), architects initiate a conceptual design through physical sketches on paper or a sketchbook. It then goes under careful CAD modeling process for detailed modeling and engineering analysis. Design in terms of engineering is also an iterative process. To create an optimal design, the engineer must develop a variety of solutions, evaluate each one, and then select the alternative that best satisfies the design requirements. During the conceptual design, the initial idea is usually altered many times. This may affect the architect's intention in terms of the original design. However, if the architects are provided with an understanding of the structural behavior of their conceptual design, they could alter the design accordingly by instantly comparing alternatives during the preliminary design phase.

Although computers have made great contributions to facilitate architectural practice, the essence of design cannot be achieved through generating forms from sets of computer instructions, and parametric assembly of segments available in most CAD software. "Architecture cannot divorce itself from drawing, no matter how impressive the technology gets" (Graves 2012). Architects' sketches express the interaction of their minds, eyes, and hands; apart from that, buildings will no longer be the outcome of visual and spatial thoughts of architects, but they would be 'computed' via interconnected databases (Graves 2012). There have been many attempts in transforming the architects' design environment into digital sketch-pad with considerable possibilities to imply creativity and produce forms. While current state-of-the-art sketch-based UIs can handle the geometry very well, few however address the needs of an engineering analysis and the possibility of manipulation, simultaneously within the same environment. A key factor to create an ideal design is to allow natural tendencies of designer to be integrated into a digital environment which can perform engineering analysis, and presents technical feedback to the user.

Within a narrower two dimensional (2D) scope, SMATS is intended to integrate structural analysis of truss systems with the architect's freehand sketching in order to facilitate the design process and improve the architect/engineer interactions. A truss is a popular structural form commonly used for covering large spaces. It is usually assumed to be made of pin-connected linear elements. Due to this assumption and loads being applied at the connections only, the members of this structural system are only subjected to tension or compression. Through the visualization of the structural analysis outcomes, SMATS can allow the user to check if the forces and deformations are within the acceptable limits, based on the engineering requirements. SMATS has three modes/states of operation: building, simulation, and animation. While in the building mode, users can sketch in an intuitive medium and explore architectural forms by freehand sketching. They can manipulate each attempt, change, adjust, or add structural elements to their desired form. In the simulation mode, SMATS performs the structural analysis of the design. The analysis results can be easily observed both visually and numerically. Other that visual representation of results, in the animation mode, users can actively view the behavior of the truss under the applied load.
Within any of the aforementioned modes, users can instantly switch to the next or previous mode and apply the desired modifications. The easy navigation through the sketching modes and subsequent analysis of the truss system provides the users an integrated medium to optimize their initial design.

1.0. SMATS SKETCH-BASED SYSTEM OVERVIEW

1.1. User interface

The UI for SMATS provides architects an interactive environment as simple as their sketchbook. Architects can create the outline of their design using a stylus in the 'building state'. While a background scaled grid gives an overall estimate of the dimensions, the user can also examine the exact length of the lines which are being drawn (Fig. 1). Once the initial outline is complete, it can be built into a 'beautified' version, in which, modification of the form is enabled. In a beautified version of a truss, the ambiguous freehand sketches are transformed into a more precise and structured representation. The user can also assign load and support conditions to the truss.

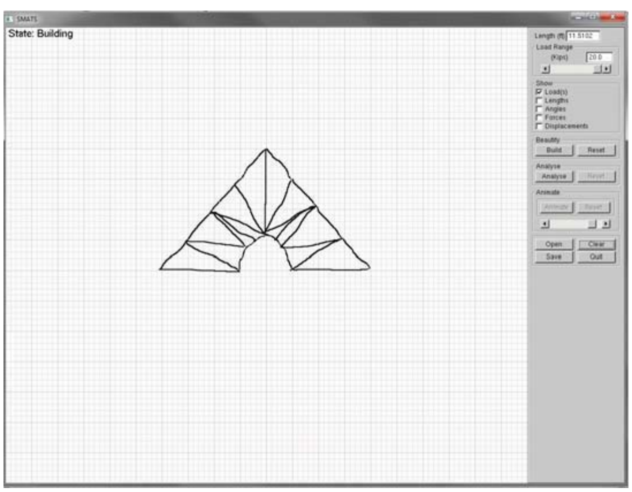
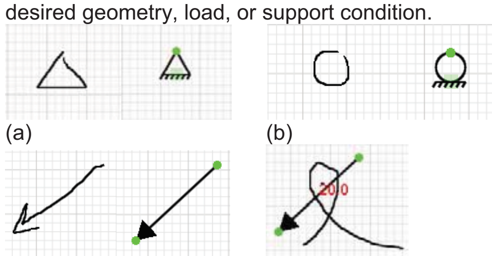


Figure 1: SMATS user interface, 'building' state. Any desired form can be drawn on the sketch pad using a stylus.

Each element of the sketched model has to be recognized by the computer before further manipulations and processing can be conducted. For this purpose the $1 Unistroke Recognizer (Wobbrock et al. 2007) is used as the gesture recognizer in order to manipulate the sketch and also determine required data for further analysis. Supports can be assigned to the nodes by drawing symbolic gestures. Sketching a triangle would be conceived as a simple support (movements not allowed, rotation allowed), and a circle would be recognized as a roller support (movement in one direction and rotation allowed). The user can also assign loads to each node by sketching an arrow in the desired direction (Fig. 2). The magnitude of the load can then be increased or decreased through a sliding bar to observe the effect of load on the structure. All the magnitudes of the loads, member lengths and angles of the loads and supports can be chosen to be viewed or not. Finally, a delete gesture enables the user to remove unwanted elements.

Once the sketched truss is fully recognized by the program, and the initial sketch is replaced by an enhanced version of the model with the standard symbols (beautified), users will have the option to either visualize the behavior of the sketched design under the assigned loads, or manipulate the design to a desired geometry, load, or support condition.

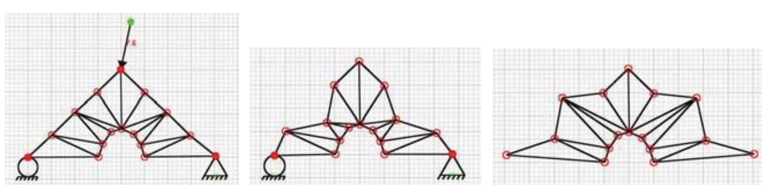


(a) (b) (c) (d)

Figure 2: Examples of symbols recognized by SMATS: (a) simple support, (b) roller support, (c) load, (d) delete gesture.

1.2. Interaction

SMATS interface enables the user to create, resize, or remove nodes and members, or supports, as well as move the position of nodes by dragging the node locators. Performing each of the stated alterations updates the data for structural analysis. Unlike many of the available literature such as 'STRAT' (Peschel and Hammond 2008): a pen-based tool for students to learn standard truss analysis, Mechanix (Valentine et al. 2012): A Sketch-Based Tutoring System for Statics Courses, 'FEASY' (Murugappan and Ramani 2009): a tool to transform, simulate and analyze finite element models, or 'APIX' (Murugappan and Yang 2011): Analysis from pixelated inputs in early design using a pen-based interface, and '2DSketchFEA' (Hutchinson et al. 2007), which is a unified framework for finite element analysis, or adaptation of it in education application: 'VisClass' (Grimes et al. 2006); in SMATS, the user is able to manipulate the sketch and apply alterations to modify form or function of the structure. The user can adjust the members, loads and supports to the desired lengths and angles, and even go back to the state of the model prior to beautification and modify the truss within its initial outline. Figures 1 and 3 show a user's attempt to design and modify a truss iteratively towards a desire form. In Fig. 1, the user has tried an initial idea which it's beautified version in shown in Fig. 3(a). Figures 3(b) and 3(c) show the user's attempted alternative configurations of the same truss members by dragging the node locators.



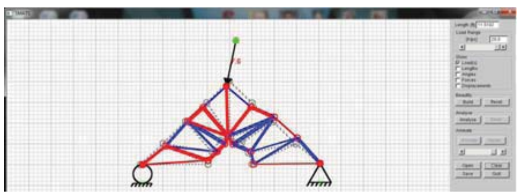
(a) (b) (c)

Figure 3: (a) Beautified truss after sketching; (b) & (c) User manipulation of the initial design.

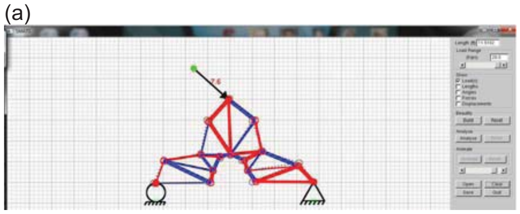
1.3. Integration of engineering analysis and visualization of results

SMATS is designed to allow the user to sketch and manipulate the sketched configuration of a truss while receiving instant feedback on its structural behavior. Once the sketched model is complete in terms of geometry and structural conditions such as load and boundary conditions, the response of the system can be simulated within the simulation mode. The Finite Element Analysis (FEA) method (Bathe and Wilson 2009) is used to calculate the internal forces and deflections of the structure. The users can then view the results directly on their drawings. The visualization of the behavioral feedback is in the form of color/thickness codes for member internal forces, and animation of structural deflections under the applied loads. Since the sketch-based interface is intended for use by non-engineers (architects), the analysis process is not apparent to the user. Only the visual results of the deformed structure will appear on the sketch-pad in real-time. Figure 4(a) and 4(b) shows the generated member internal forces of the trusses shown in Fig. 3 under an applied load. The members under tension are colored in blue and compression members are in red. The thickness of each member represents the relative magnitude of the internal force of that member in comparison to the other members. In the simulation mode, the user is also able to view the exact amount of internal forces in each member, or the amount of displacement for each node. The final mode in SMATS is the animation mode, in which the user can observe the figurative deformation of a sketched truss subjected to the assigned loads. At this stage, by observing the overall deformation of the truss, the architect can better comprehend the inter-relationship between the form and function of the design and adjust it based on the information provided by SMATS.

SMATS is a self-training UI where an architect can gain engineering perspective on the structural behavior of forms through using the program iteratively. Due to its intuitive, sketch-based design, the training period for SMATS is substantially shorter than the traditional menu-driven software tools. Once the data is updated, the users receive instant feedback about the effects of that change on their design in terms of structural behavior. Users can visualize the new results through the color/thickness codes and animation. This gives them the ability to compare different configurations and optimize the design both aesthetically and structurally. For example; one configuration might collapse under a certain load, but by changing the configuration or adding/replacing the supports, the structure would become stable under the same loading condition.



(a)



(b)

Figure 4: Simulation mode: (a) Color/thickness coding of the initial design; (b) Color/thickness coding of the modified design.

2.0. APPLICATION

SMATS is an integrated design system which contributes to both architectural and engineering designs. It provides an intuitive environment for the architects to be creative and not get distracted by the complicated menu based CAD software while using their relatively familiar pen and paper design medium. The digital ink and sketchpad which the system provides, proves to be better than traditional pen and paper in some aspects, such as, it is easier and faster to edit. In addition, every design attempt can be saved for future reference. This helps with improving productivity of the initial sketches to a great extent. Furthermore, SMATS provides a very fast and easy to use engineering analysis medium, in that it performs real-time calculations with minimum required manual input.

2.1. Application in practice

Application of SMATS as a design tool in construction industry is considerable. The system provides integrated medium for multidisciplinary design incorporating aesthetics, and structural characteristics. Therefore, SMATS can provide an environment in which architects and engineers may interact more efficiently towards a holistic outcome during the preliminary phase of design. SMATS maintains a common ground in design process for both architects and engineers to communicate ideas and make design decisions more effectively.

2.2. Application in education

Iterative usage of SMATS as an integrated design tool greatly contributes to the education of young architects. SMATS does not require any prior engineering knowledge from the user, and avoids complicated analysis and design environments. It can also help architects and architecture students gain a better understanding of the relationship between the form and structural behavior, and as a result acquire engineering intuitions from their design trials.

CONCLUSION

The present work is part of an ongoing collaborative research effort in the area of architecture, structural engineering and computer science to develop sketch-based tools which enhance integration in the preliminary design of structures. The ultimate goal of this project is to enhance creativity through optimization of the overall design process. This allows architectural freedom to create forms, and better comprehend their relationship to structural behavior, without the need to learn or concentrate on the software-specific tools. Such integration is valuable as a common language in facilitating the interaction between professional architects and engineers. Also, the iterative nature of the design process in the presented system allows the designers to be creative and provides them feedbacks as related to the structural behavior. This is a great asset in educating architects to integrate engineering requirements into their conceptual design.

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