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Technical section

Image centric finite element simulation

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Abstract

Images have played a substantial role in documenting historical structures and structural systems. As a result, extensive archives are now available to reconstruct both modern and ancient buildings, bridges and other structures for subsequent analysis and visualization. While common approaches require the creation of complex three-dimensional models to facilitate the study of response to anticipated loading of a target system or subsystem, faster techniques are required for preliminary data analysis. This paper presents an image-based approach that allows users to sketch structural systems over a reference image while using standard engineering symbols and nomenclature. Within the presented framework, the response of the sketched system is analyzed and presented using an image-centric finite element analysis approach. Finite element models of the sketched structural system and image are constructed and simulation results fused into a final visual encoding, using deformation patterns and image warping. Results for two example structures illustrate the intuitive modeling capability that the system provides to the user. The presented system is particularly beneficial in educational environments, where fundamental behavioral characteristics of structural systems are studied.

Keywords: Finite element analysis; Sketch-based input; Image warping; Scientific visualization

1. Introduction

Images have been pervasive throughout human history and have been used to capture physical systems that are now available in archived form, as carvings, sketches, paintings, drawings and photographs. In particular, images can realistically capture the attributes of structural systems and subsystems, such as their scale and spatial relationships between components and material properties. Most major structures in the world are now broadly archived in image form, indexed and cross referenced and are therefore easy to obtain [1–3]. Furthermore, over the past century, image sequences have also captured the systems' change including construction, movement under loading and deterioration. These archives are now widely used to reconstruct and analyze entire structures or structural components based on the information encoded in the available image records. Traditional approaches to reconstruction consist of creating texture mapped three-dimensional (3D) geometric models by correlating information available within the images, or using them to create finite element meshes for subsequent analysis. However, this approach has proven to be a very complex and time consuming process.

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It is desirable to perform conceptual studies directly and rapidly on the original image, removing the need for extensive and time consuming 3D modeling, meshing and analysis. To this end an image-based approach is proposed in this paper, that enables the study of the response of structures where all processes, including modeling, analysis and response visualization, are centered around a user selected reference image. The presented approach allows users to sketch the structural system over a reference image using standard engineering symbols and nomenclature and to subsequently simulate and analyze the responses of the sketched system under various loading conditions using a finite element approach. Once simulation results are available, they are mapped onto the original drawing, providing the user with an interactive and physically meaningful sketching and simulation environment.

2. Related work

The presented approach contributes towards and draws from different domains, including sketch-based input, image-based finite element analysis (FEA), and image warping. As such, the following review of the literature addresses relevant work in each of these three areas.

2.1. Sketch-based investigations

Typically, even when a reference image is available, 2D models are constructed by hand. Ju and Hosain [4] present a system that allows users to build FEA models in this way. The tool integrates FEA and its stick-figure representation, by allowing users to draw nodes and boundary conditions and to connect them with lines using a typical windows, icons, menus and pointers (WIMP) drawing approach. The tool allows the created system to be simulated and displays the resulting nodal displacements within the same window. By now, many commercial packages used in practice have this concept as their basis. Examples include SAP2000 [5] and RAM Steel [6]. In a similar fashion, many computer-aided design (CAD) tools have included sketch-based methods into the traditionally drafting-based CAD, however, the degree of integration varies. For instance, PTC's Pro/CONCEPT [7] allows both traditional CAD-type and sketch-based input utilizing a digitizer pad, however, sketches are restricted to pre-existing surfaces.

Buchal [8] claims that sketch-based input is not necessarily better than traditional WIMP-based CAD input for conceptual design, and that, in many cases, newer CAD tools are more effective. However, the mechanical drawings that Buchal investigates are at the component level rather than at the system level. Since the focus in this paper is on simulating structural systems, it is reasonable to use sketch-based tools as a CAD alternative for constructing these systems.

Different sketch recognition algorithms have been introduced over the past few years and are now available in the form of libraries that support shape recognition. An example of such a library is the CALI engine [9], which was designed to provide general sketch recognition support to a wide range of more specialized sketch-based interfaces. Similarly, Alvarado et al.'s recognition framework [10] is designed to facilitate the recognition of sketches from multiple domains. They propose that low-level shape recognition and high-level domain-specific recognition should be kept separate, a concept that we have employed. A major difference between their work and ours, however, is their use of Bayesian networks and other probabilistic methods to determine user intent. This is necessary for domains where sketching practice varies much more widely than it does in engineering mechanics. Apart from what occurs in the low-level shape recognition, we employ no probabilistic calculations or fuzzy logic, and have attempted to avoid heuristics.

2.2. Image-based FEA

It is possible to automatically generate a 3D finite element model when sufficient image data is provided. Work by Popescu [11] considers many techniques to convert images into 3D models (image-based rendering), while Lee et al. [12] developed a method to automatically generate finite element meshes from constructive solid geometry (CSG). Techniques for the construction of finite element meshes from medical images have been used to study different portions of the human body. For example, Kwon et al. [13] illustrate a nearly automated approach to generate a tetrahedral finite element mesh from images obtained with computed tomography (CT) or magnetic resonance imaging (MRI) techniques. Similarly, Parker et al. [14] focus on reconstructing meshes from images of human arteries. Given available voxel datasets from tomograms, Hartmann and Kruggel [15] generate 3D finite element meshes of the human brain. These approaches differ from the one presented in this paper, in that they focus on dealing with larger dimension 2D or 3D meshes, use a different image basis, prioritize automation aimed at no user intervention and as such are frequently subjected to problems introduced through faulty automated mesh generation requiring user intervention at a later point.

Select information regarding structural characteristics of a system can be obtained from the image itself. For example, Danielson et al. [16] used images to determine enough geometric information to calculate the cross sections of tires. These data then serve as input into a 2D finite element mesh. Sienz et al. [17] demonstrate extraction of a cloud of points from various image