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Real-time finite element structural analysis in augmented reality

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ABSTRACT

Conventional finite element analysis (FEA) is usually carried out in offsite and virtual environments, i.e., computer-generated graphics, which does not promote a user's perception and interaction, and limits its applications. With the purpose of enhancing structural analysis with augmented reality (AR) technologies, the paper presents a system which integrates sensor measurement and real-time FEA simulation into an AR-based environment. By incorporating scientific visualization technologies, this system superimposes FEA results directly on real-world objects, and provides intuitive interfaces for enhanced data exploration. A wireless sensor network has been integrated into the system to acquire spatially distributed loads, and a method to register the sensors onsite has been developed. Real-time FEA methods are employed to generate fast solutions in response to load variations. As a case study, this system is applied to monitor the stresses of a step ladder under actual loading conditions. The relationships among accuracy, mesh resolution and frame rate are investigated.

1. Introduction

Numerical simulation has been widely conducted by engineers to analyze and predict the behavior of real-world physical systems. As a versatile tool, finite element analysis (FEA) has been implemented in various fields of engineering, such as structural mechanics, electromagnetics, heat and fluid flow. Nowadays, almost all practical FEA studies are completed with the help of computers and professional software, such as ANSYS, Abaqus and COMSOL. Benefitted by the well-developed computational techniques, such as automatic mesh generation and scientific visualization, engineers are able to handle complex modeling and result interpretation easily.

However, traditional computer setup has limited the FEA processes, from model building to result display, in a totally virtual and offline environment. The virtual environment deprives the human senses of the physical characteristics, such as scale, orientation and material, and the surrounding physical context is usually not provided. It is not intuitive and efficient to examine and interpret FEA results without senses of scale and the necessary context. Before performing FEA, engineers must obtain proper loads and boundary conditions (BCs). To acquire these parameters in an actual operating environment, measurements can be conducted onsite, for instance, measuring the load variations on a crane with load cells. The load data will be processed and transferred into FEA systems, which usually involves some tedious and error prone tasks, such as manual data transfer and coordinate transformations, and the results are obtained offline.

Another problem lies in the interactivity. Traditional FEA usually consists of three steps, i.e., pre-processing, solving and post-processing. In the pre-processing stage, a mesh model is created and the relevant parameters, such as loads, material properties and constraints, are prescribed, normally via manual entry. Next, the FEA system builds and solves the equations. The results are post-processed and displayed according to user's requirements. The computation time depends largely on the number of nodes and the processor performance. There is always a tradeoff between model accuracy and computation time. In practice, most FEAs tend to achieve accurate and detailed results by using fine meshes and nonlinear models, which would certainly require considerable computation time. Users usually have to repeat certain standardized steps to cope with parameter variations. Traditional FEA systems thus have weak interactivity. In a number of situations, FEA systems are expected to update results efficiently in response to parameter variations, e.g., geometry modifications in product design [1]. Real-time performance is required in certain special applications such as interactive entertainment and surgery simulation [2]. This demand motivates the development of real-time interactive FEA technologies.

Augmented reality (AR) technology has been developed in the last two decades to enhance a user's perception of and interaction with the real world. AR supplements reality by superimposing

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computer-generated information, such as graphics, texts and audio, over the real-world environment in real time. AR allows the utilization of physical objects, the properties of which cannot be sufficiently embodied in a virtual FEA environment, e.g., scale, orientation, etc. An intact physical context is also preserved for reference. Superimposing FEA results on the corresponding real objects will facilitate results exploration and interpretation. The onsite environments also make it possible to acquire loads and BCs directly using proper sensors and instruments. Tangible interfaces can be developed for intuitive user interaction.

With the goal of utilizing AR technologies to assist structural analysis, this paper proposes a novel system which integrates FEA simulation, scientific visualization and load measurement into an AR-based environment. Unlike traditional FEA systems, the integrated system is able to acquire load data directly from real-world environments, and the deformations and stresses of structures are simulated in real time. A wireless sensor network (WSN) is established and registered onsite to acquire spatially distributed loads. The real-time FEA results are superimposed on physical structures to give lucid illustrations. The rest of the paper is organized as follows. A review of related studies is given in Section 2. Section 3 elaborates the architecture of the integrated system, as well as the relevant methodologies. The proposed system is implemented with a case study in Section 4 followed by a discussion in Section 5, and conclusions are drawn in Section 6.

2. Related works

2.1. Interactive FEA in virtual reality

To overcome the shortcomings of conventional FEA environment, virtual reality (VR) techniques have been employed by many researchers to achieve immersive environments. Various visualization approaches and interactive applications have been developed. Scherer and Wabner [3] proposed a method to visualize FEA results and constraints with stereoscopic visualization methods and glyph-based display, in order to improve human perception and comprehension of complex datasets. Hafner et al. [4] introduced an approach for post-processing electromagnetic solutions in VR. By using Visualization Toolkit (VTK) [5], interactive cutting and operating of solution data are achieved. The FEMvrml system built by Lee and El-Tawil [6] adopted Virtual Reality Markup Language (VRML) to visualize the results of structural analysis for internet. Java-based interactions were developed to control and explore the animation prepared beforehand.

With the goal of integrating VR technologies in the entire product design process rather than only post-processing CAD models and FEA results, Ingrassia and Cappello [7] developed a system called VirDe, which allows the designers to perform the design processes, including CAD modeling and FEA simulation, in a VR environment. To facilitate the architecture students and practitioners' understanding of the structural behaviors of buildings, Setareh et al. [8] presented an application which allows the users to build structures and simulate the effects of various environmental loads. Standard FEA programs are adopted in these two systems, such that the users have to repeat the FEA processes for parameters changes. In contrast, interactive FEA applications are more efficient and immersive. Connell and Tullberg [9] presented a framework for the integration of FEA simulation and visualization within VR. To achieve real-time response for changes on loading patterns, an approximation module is established to generate simplified results efficiently before accurate results are available. Ryken and Vance [10] created a VR application for the design of a tractor arm in a CAVE-like system. In this application, the designers can modify the shape of a component and view the updated stresses interactively. With a sensitivity analysis carried out beforehand, a linear interpolation was implemented to approximate stresses in real time.

2.2. Numerical simulation in augmented reality

Compared with VR, the most definite advantage that AR provides to numerical simulation is the visualization of various datasets with real-world backgrounds. In the ARVIKA project [11], AR technology was used to support immediate comparison of the real and simulated results of a vehicle crash test, such as stress, strain and internal energy, by overlaying simulated results on a crashed vehicle. To visualize industrial engineering data in AR, Bruno et al. [12] developed a framework, called VTK4AR, that provides a set of classes for the AR visualization of scientific datasets with the VTK. Buchau et al. [13] applied AR technology in the context of teaching electrodynamics in a lecture room. In this system, 3-D magnetic fields and electromagnetic fields are prepared with FEA software, and imported to a special visualization system for the AR environment, namely, COVISE. Weidlich et al. [14] visualized the FEA results of machines with a mobile AR system. The reported system has a client–server architecture in which the server reads the data, generates the mesh and calculates the result. The client performs result rendering and some interactive functions for visualization. Taking the advantages of mobile AR systems, Heuveline et al. [15] presented a system for outdoor applications. A computational fluid dynamics (CFD) simulation of urban buildings was carried out on a server. An AR visualization of the results was displayed on smartphones using a hybrid tracking technique. Besides visualization, AR can also be used in collaborative environments for multiple users. Uva et al. [16] augmented traditional 2-D technical drawings with FEA simulation results and annotations. The web-based application enables multiple users to work collaboratively. Each client can explore CAD and FEA data, and create annotations on the augmented drawings. Modifications of annotations are synchronized instantly among the users, and converge to a new design finally.

However, in these reported applications, the physical surrounding is merely a site to render the simulation results. The advantages of AR environments are not fully utilized. Indeed, AR environments allow simulation systems to acquire parameters from the real world directly, resulting in more intuitive user interfaces. Niebling et al. [17] presented an AR application for the prototyping of a water turbine. In this application, the users can adjust the rotational angle of real turbine blades, which leads to parameter changes that have to be input to the CFD software for simulation so as to update the CFD results that are superimposed on the turbine. This application allows the efficient investigation of blade angles for different operating conditions. In a project carried out at the University of California at Davis, an AR sandbox [18] has been developed for teaching earth science. With this system, the user can create topography models by shaping real sands, and a water flow simulation is performed responsively with the depth frames captured using a Kinect camera.

In large-scale numerical simulation, a detailed or stable simulation usually causes time delay to interaction. For those models of which real-time simulations are possible, the interactivity provided by an AR environment provides more attractive features because the user can receive feedbacks which are correct both in space and time. Fiorentino et al. [19] reported an interactive simulation approach for engineering education in AR. Their approach updates FEA results with changes in displacement BCs tracked using a camera. Tests were implemented on a cantilever that is deformed by hand. By using the COMSOL software, FEA results were refreshed at a rate of 6.5 Hz for a mesh of 132 nodes. More evaluations of this tangible simulation approach can be found in