Int. J. Engng Ed. Vol. 25, No. 6, pp. 1124–1128, 2009
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Interactive 'touch and see' FEM Simulation using Augmented Reality*

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This paper presents a novel 'touch and see' approach for interactive teaching of dynamic stress/strain distribution in engineering education. Our Augmented Reality application visualizes Finite Element Method (FEM) results overlaid over the real model. The user can interactively change the boundary conditions of the simulation and then evaluate the stress distribution in real time. Marker based video tracking is used to measure displacements while COMSOL Multiphysics solves the structural FEM analysis. A cantilever test case has been implemented and evaluated. We describe the optimization solutions needed to achieve real-time simulation and precise and stable tracking. The presented system demonstrates significant educational benefits making the student's experience more attractive and effective.

Keywords: augmented reality; active learning; FEM; tangible interfaces

INTRODUCTION

ACTIVE LEARNING is a well known approach that uses hands-on experiences to improve students' overall learning. Although the importance of active learning activities is scientifically proven, little effort has been spent on the development of an Active Learning Product (ALP) in an engineering curriculum [1].

For example, among the ALPs for engineering education, 'photoelasticity' is commonly used in teaching stress distribution, with the clear advantage that the students can interactively apply forces to the model and visually understand the stress effects [2]. But this 'touch and see' method requires a rather complex set up: first the test part should be optically transparent and coated with a strain-sensitive paint, and secondly it should be subjected to an external load and observed with a polariscope (see Fig. 2). The strains throughout the part are transferred to the coating and observed as optical fringes.

Augmented Reality (AR) technology has been successfully used in engineering education by Salzmann *et al.* [3] for real-time control solutions. Their system demonstrated the feasibility of a flexible virtual laboratory for distance learning.

Our approach explores the Augmented Reality (AR) technology to provide a novel interactive way of showing dynamically the stress/strain distribution over a real model. By mimicking a photo elastic bench, our AR setup augments the real model with simulation data coming from FEM analysis.

Interactivity is a decisive aspect in FEM simulation due to the natural 'trial and error' process in engineering design [4, 5]. An interesting approach to explaining complex nontraditional manufacturing processes has been presented by Yao *et al.* [6]. They studied the interactive exploration of physical processes and simulations using 3D web technologies, multimedia and virtual reality.

In our educational approach we want to stress the interactivity up to real time in order to raise interest and increase motivation in the students and enhance the learning experience. The basic idea is to develop an easy to use setup where the user can change the FEM boundary conditions by deforming the real model and evaluate the simulation results in real time (i.e. touch and see). As shown in Fig. 3, a digital camera acquires the real scene; the system evaluates the model deformation using optical tracking, then it updates the model geometry and FEM simulation and finally it overlays the results on the real model. We tested this approach on a common educational example: a cantilever deformed by the user (see Fig. 1). The system detects, in real time, the position and orientation of the two cantilever extremities and it updates the boundary condition in the FEM simulation. This approach is known as 'displacement control' instead of the common 'load control'.

Although the literature reports several applications of AR engineering data visualization [7, 8], none of them is specifically aimed at the creation of hands-on active learning products for engineering education.

Therefore, this work takes a step in this direction by making three main contributions: (i) the use of AR to overlay the FEM results (i.e. a color map) directly on the physical model; (ii) the optimization of an FEM solver connection bridge to achieve real-time simulation and; (iii) the optimization of optical tracking for measurement of displacements to control the FEM simulation. In the next sections we will present each of the aforementioned aspects in detail.

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* Accepted 12 August 2009.

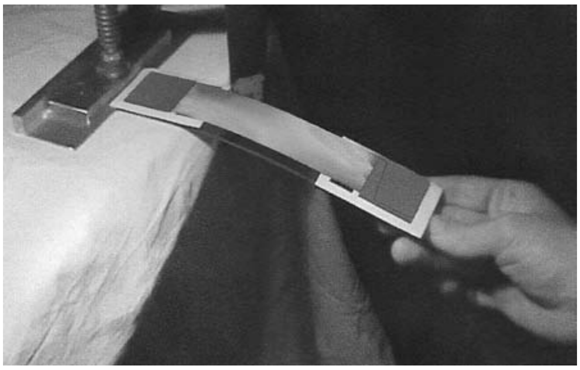


Fig. 1. Interactive ‘touch and see’ stress visualization using Augmented Reality.

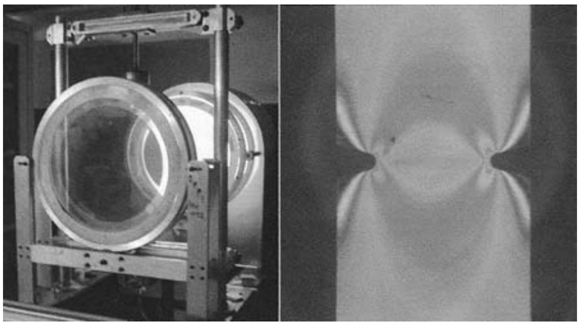


Fig. 2. Photoelasticity bench for visualizing stress configuration.

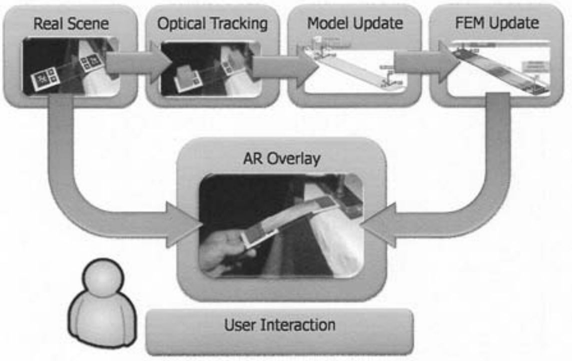


Fig. 3. The proposed idea: interactive FEM simulation in Augmented Reality.

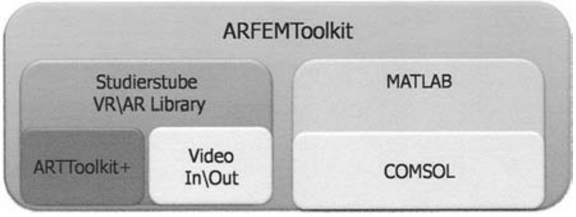


Fig. 4. ARFEMToolkit software architecture.

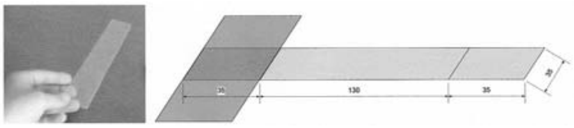


Fig. 5. Cantilever bar dimensions and constraints.

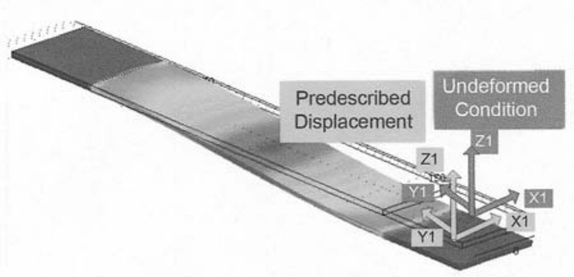


Fig. 6. COMSOL simulation: un-deformed and deformed geometry

AR VISUALIZATION INTEGRATION WITH FEM

We developed an application called the ‘ARFEMToolkit’ to integrate an FEM solver into an AR based visualization system. The ARFEMToolkit uses a modular architecture in C++ (see Fig. 4). The application is based on two main modules: the first manages user interaction, visualization and video overlay, the second handles the simulation. We decided to use the StudierStube library [9] for flexible AR visualization and interaction, and the ARToolKitPlus [10] for the marked based optical tracking. We chose COMSOL Multiphysics^{TM} bridged with MATLAB^{TM} for the structural FEM analysis. We tested several FEM solvers but we found that, due to the unique I/O communication capability, COMSOL (in particular, the Structural Mechanic module) was the choice for interactive simulation. The native integration of COMSOL with the MATLAB scripting system allows our ARFEMToolkit to access any step of the solver process. Most of the available FEM solvers, (i.e. Ansys^{TM}) base their I/O operations on disk file access, making it impractical to modify the solution in real time.

SIMULATION DETAILS

We decided to use the linear static analysis of the Structural Mechanics Module of COMSOL with Argyris shell elements. We modeled the cantilever geometry in COMSOL (Fig. 5) from the real transparent non-reflecting polystyrene bar and associated the material properties.

The constraint system is composed of a ‘Fixed’ end (left side in Fig. 5) and a ‘Predescribed Displacement’ condition on the free end. This displacement (translation + rotation) is updated in real time according to the optical tracking data (Fig. 6). No load conditions are applied.

We generate a finite element representation of the beam structure (i.e. the nodes and element connectivity) using a triangular free mesh to allow for other educational shapes (i.e. V-notch).

Our application uses optimized MATLAB

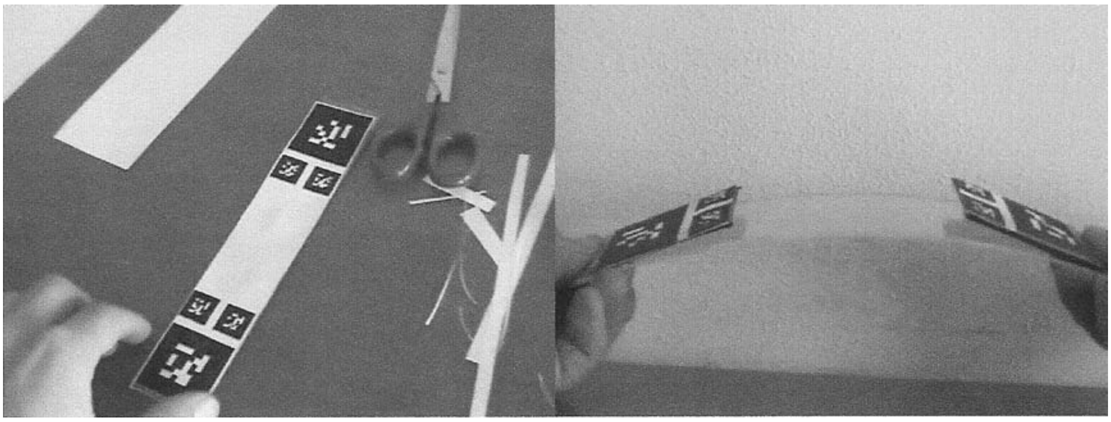
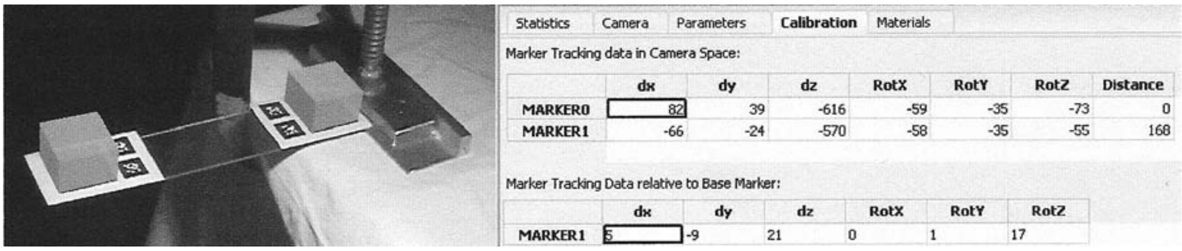


Fig. 7. Multimarker configuration used for cantilever test.



Marker Tracking data in Camera Space:

	dx	dy	dz	RotX	RotY	RotZ	Distance
MARKER0	82	39	-616	-59	-35	-73	0
MARKER1	-66	-24	-570	-58	-35	-55	168

Marker Tracking Data relative to Base Marker:

	dx	dy	dz	RotX	RotY	RotZ
MARKER1	5	-9	21	0	1	17

Fig. 8. Multimarker recognition (augmented boxes) and test panel.

scripts to gain real-time access to COMSOL to set/change the boundary conditions and to retrieve FEM solutions data (see Fig. 6). The results of the analysis (i.e. von Mises stress) are converted, according to user preferences, into a color map and conveyed to the AR visualization module.

REAL TIME ISSUES

Beside the static visualization of FEM data, an important aspect in the learning process is to allow the user to change the simulation parameters and to evaluate the results immediately. Therefore, one of the main challenges is to obtain interactive simulation and visualization. AR real time interaction requires a visualization update of a minimum of 15 frames per second. In a closed loop approach, new solution data must be available to the AR viewer with at least 15 Hz. The parameters that condition this frequency are the FEM solution time and the time spent in communicating the data to the AR viewer. If the FEM data are not available with such a frequency, the FEM solver will have to work asynchronously. For this reason the ARFEMToolkit is specifically designed to work using separate threads (decoupling the simulation process from the visualization one), fully exploiting the potential of a multicore architecture CPU.

In order to get real time performances in our tests, we had to optimize the MATLAB-COMSOL bridge using specific software tricks to reduce communication and simulation time. The main achievements are in (i) avoiding model remeshing, (ii) reducing the use of a garbage collector and (iii) rewriting some functions calls. We use a statistics panel to visualize the CPU time for: (i) AR visualization and optical tracking, (ii) FEM model boundary condition update and (iii) FEM solution. This low-level optimization allowed a significant reduction of up to 93% of computation time.

TRACKING OPTIMIZATION

Scene tracking plays an important role in AR applications because it allows the exact overlap of the virtual models onto the real world. Bad tracking can lead to a very uncomfortable experience for the user: virtual objects can be disconnected from their virtual counterparts, the 3D virtual scene may flicker or have wrong context recognition, etc.

In our application we use tracking not only for AR registration, but also to measure the displacements to control the simulation. This requires high precision (<1 mm in the proposed test case) and stability to guarantee a sound input for the simulation. We use marker based optical tracking because it requires the same camera video stream used for the video overlay. This kind of tracking needs a camera calibration procedure before operation and unique ID markers have to be physically applied to the object of interest.

First tests demonstrated that single marker setups do not allow for sufficient precision and stability. We tested different marker configurations by changing marker number, border width and size. The best results were obtained using multimarkers (a set of three markers that work as a single more precise marker, see Fig. 7, left). We also observed a remarkable increment in precision/stability by applying each multimarker on a carbon fiber support. This result can be explained because the base ensures planarity during user interaction (see Fig. 7, right).

Figure 8 shows the multimarker test panel with position and orientation values updated in real time (right) and the exact overlay on the real model (augmented boxes on the left). We use this panel to test the camera calibration and exact registration between the real and virtual models.

PERFORMANCES

We tested the ARFEMToolkit in order to evaluate: (i) if such an application can really be considered real time 'interactive'; (ii) its usability as an educational tool. As far as regards the interactivity, we ran the application using a laptop setup (Toshiba Satellite A100-206, Centrino Duo T2300, 1 GB RAM, Ati Mobility Radeon X1600). This setup was used as it provided a portable system to be used in any classroom. We measured an average FEM simulation refresh frequency of 6.5 Hz (132 nodes mesh). Owing to the asynchronous behavior of our software architecture, the rendering refresh rate was always above 30 Hz.

EDUCATIONAL GAIN

We ran qualitative tests with 20 graduate students from the Mechanical Engineering Faculty at Politecnico di Bari, Italy. Most of the subjects (90%) rated the application very useful for better understanding of the mechanics of materials. Only two subjects reported some delays in the simulation refresh, while all the others were unaware of the simulation latency in the background.

The proposed approach to Active Learning using AR pinpointed several educational advantages.

The 'touch and see' approach allows the students to interactively apply forces to the model and visually understand the effects. Unlike other ATLs (i.e. photoelasticity bench), simulation data can be displayed according to user preferences and changed even at runtime (i.e. arrows, streamline, slices, etc.)

Another advantage is related to the simple hardware setup (PC and digital camera), which is easily accessible without the need for expensive laboratory equipment.

Moreover, removing the barrier between real and virtual simulation allows students to explore and to interact with the model, making the classroom experience more attractive and effective.

CONCLUSIONS

We presented an Augmented Reality approach to provide an interactive 'touch and see' FEM simulation tool for engineering education. The proposed system visualizes FEM results as overlaid over the real model. The user can change the boundary conditions of the simulation hands-on and then evaluate the stress distribution in real time. We tested this approach on a cantilever. Three main results have been achieved: (1) a real time overlay of FEM results directly on the physical model; (2) asynchronous multithread optimization of the FEM/AR connection bridge and; (3) effective use in teaching material behavior.

The results depend drastically on the precision and stability of the tracking system. Therefore, high resolution cameras with good quality optics, precise marker print and accurate camera calibration are mandatory. At the moment one limiting factor is the model complexity which significantly affects the simulation time. The proposed approach will be applicable to more and more complex models, as long as the increase of computing power and new simulation algorithms allow.

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