AR APPLICATION FOR PRE-POST PROCESSING IN ENGINEERING ANALYSIS FOR NON-EXPERT USERS

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The aim of the work presented in this paper is to develop and test new interaction paradigms based on Augmented Reality techniques for handling parameters and results in the pre and post-processing phase of engineering structural and computational fluid dynamics analyses to be used even by non-expert users. This would allow non-expert users to understand the phenomena through a straightforward cause-effect approach that is commonly recognized as an enactive process. In the paper we describe the development of the application and some preliminary users' tests that have been used to validate the approach proposed.

Keywords: Augmented Reality, Product development, Engineering analysis, pre-post processing.

1. INTRODUCTION

The typical product development process (PDP) starts with the conceptual design of a new product, where its overall architecture, shape and general functions are defined. These activities are typically carried out by industrial designers. The following embodiment design phase takes the conceptual design decisions made in the previous phase and transforms them into a product that can actually be produced. The decisions that are taken at the embodiment design phase have to be justified by mathematical and physical proofs, as much as possible. For reasons mostly related to costs, this is today usually done through computer-based simulations instead of using traditional physical prototypes [1].

For these reasons, the phase following the embodiment design is a phase dedicated to analysis and simulation, where numerical and engineering analysis methods are used to reveal and proof the various properties of the new product. Several analysis methods are used for checking various properties of the product. Structural analysis and fluid-dynamic analysis are just some of them; those are the ones addressed in this paper. Structural analysis applies physical laws to study and predict the behavior of engineering artifacts, mainly in terms of deformations, internal forces and stresses. Fluid-dynamic analysis studies those problems that involve movement of fluids around and inside objects.

Nowadays, several tools support these analyses: structural Finite Element Methods (FEM) tools and Computational Fluid-Dynamic (CFD) tools have been developed since the 70s [2]. The use of these tools is typically accompanied by a pre-processing phase where the analysis parameters are set, and a post-processing phase where the results of the analysis are evaluated. The analysis tools require a fine and time-consuming setting of the analysis parameters and they also take high computational time for computing the results and for any re-run of the simulation with different parameters.

Typical users of these tools are expert analyst engineers who well know the phenomenon to model and simulate, and also how to use the tools for setting the parameters for reproducing the phenomenon.

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Indeed, these tools are not suitable for novice analyst engineers who are learning how to perform FEM and CFD analysis, or students who have to learn and understand the various phenomena related to structural and fluid-dynamic behaviors of objects.

The aim of the work presented in this paper is to develop and test with users new interaction paradigms based on Augmented Reality techniques for handling parameters and results in the pre and post-processing phase of FEM and CFD analysis to be used by non-expert users. This would allow them to understand the phenomena through a straightforward cause-effect approach that is known as enactive process in the Human-Computer Interaction context [3].

Several research works reported in literature have demonstrated that the use of the rapidly developing Augmented Reality technologies integrated with interaction paradigms based on tangible interfaces facilitate the interaction with 3D models and simulation data [4, 5], and in addition that enactive interfaces successfully support applications where users can learn by doing [3]. In our work, we have investigated and evaluated the potential benefits of using these interaction paradigms in the product engineering analysis context.

2. RELATED WORKS

This section presents state of the art research in the domains of Augmented Reality applications developed for supporting industrial product development. Recently, in the field of product development several research groups have developed applications based on Virtual and Augmented Reality in order to improve, speed and simplify the various development phases. Augmented Reality (AR) is a growing research topic within the Virtual Reality research area and addresses all those technologies that allow us to integrate virtual objects or information with the real environment [4]. This is basically accomplished by an analysis of the real environment that allows us to capture some geometrical information, and process them in order to align correctly digital and real information. Real environments used for Augmented Reality applications can be structured or unstructured, i.e. equipped with some fiducial markers and recognizable elements or not [6].

ARToolKit [7] is a popular library that implements the real-digital objects alignments by means of cheap commercial cameras and printable bi-dimensional markers. The environment is structured in a way that some markers are located in precise positions in the environment. The algorithms of ARToolKit analyze the acquired images, identify the fiducial markers and for each of them compute position, orientation and distortion parameters of the camera. Then, in the visualization rendering window real and virtual information is merged. Other tracking libraries have been developed that make use of marker-less technologies. Another trend concerns the integration of the visualization technologies with other measuring instruments like accelerometers, inclinometers and gyroscopes.

Regarding the technologies for rendering combined real-virtual information it is possible to use common monitor displays, hand-held displays or Head Mounted Displays (HMD). An effective visualization system is represented by the stereoscopic Video See-Through Head Mounted Display devices that allow us to see the real environment — which is acquired by two cameras — augmented with digital information in a three-dimensional modality. Unfortunately, up to now most of these devices are still academic prototypes [8] or are often developed for specific application cases; but recently some light, ergonomics, low cost and performing goggles have been developed and put on the market [9].

AR technologies have proved to be effective in the product design domain: Virtual Prototypes of new industrial products made of both real and virtual components allow us to perform evaluation tests of functional, usability, and ergonomics aspects of these products without the need to build expensive physical prototypes. In Bruno *et al.* [10] it is described the possibility to see the results of a CFD analysis directly displayed onto the physical prototype of the product by using a tablet pc. More recently Faas [11] has presented a work where a real-time structural analysis is performed on a model deformed by means of a haptic interface.

The kind of interaction offered by AR applications has demonstrated of being effective for a more natural use of traditional applications, but still presents several open issues. Research is focusing on investigating the possibility to improve the interaction with AR environments, including and experimenting multiple interaction modalities that enrich and make more intuitive and natural the use of applications.

3. AR APPLICATION

This section describes the application that we have implemented for pre and post processing engineering structural FEM and CFD analyses. The application is based on Augmented Reality techniques, with the aim of developing easier and more natural interaction modalities oriented to non-expert users for performing cause-effect kinds of studies where the parameters are set and the results are evaluated in a close loop. The application makes use of simple and low cost technologies, while supporting natural and direct manipulation of objects and effective stereoscopic visualization of the simulation data. In addition, computational speed of the simulation is a priority with respect to accuracy.

Our study started from the analysis of current structural FEM and CFD tools (Nastran, Ansys, Fluent, Comsol, etc.), where we have detected a clear complexity of the user interface for setting the analysis parameters and for accessing the analysis results. On this basis we have defined a set of features and functionalities for a new application based on novel AR technologies, where interaction is more user friendly.

3.1. Application Interaction

The features of our AR application are as follows.

1. *TUI manipulation of the target object.* AR visualization integrated with tangible user interface (TUI) is used for moving and orienting the object to analyse. Users can directly rotate a physical object for rotating the virtual object. The object and the simulation data are contextualized with the real scene, for a better perception of the phenomenon. In fact, simulation data may be super-imposed onto the real environment or onto a real system.
2. *Multimodal interaction with object and simulation parameters*. A multimodal user interface allows direct interaction with object geometry and setting numerical parameters according to a "learning by doing" paradigm. The application integrates a 6DOF interaction device allowing for manual interaction and tactile feedback of performed actions, supporting an easy selection of visualization modalities of analysis results, and allowing direct pointing at points/areas on object surface and simultaneous setting of numerical values of parameters. For example, tactile feedback related to the load set in a point is rendered through a vibratory cue provided by the 6DOF interaction device that reproduces the contact with a virtual object.
3. *Real-time computation of the engineering analysis*. In order to allow a real-time interaction with the simulated phenomena, the application should compute the simulation results and presents them to users in real-time or anyway in a very short time.

3.2. Application Functionalities

The application is based on an interaction flow including input from the user, computation, and output to the user. The interaction flow is shown in Figure 1. The user can set the position and orientation of the virtual object, as well as use a 6DOF input device for pointing at the application space. In addition, the user is able to activate command functions (for example, start simulation command). The system computes the virtual object position and orientation and the feedback values about contact with the virtual object, and performs the requested analysis. The resulting data are integrated and mixed, and communicated to the user through various devices (AR visualization device, tactile device, etc.).

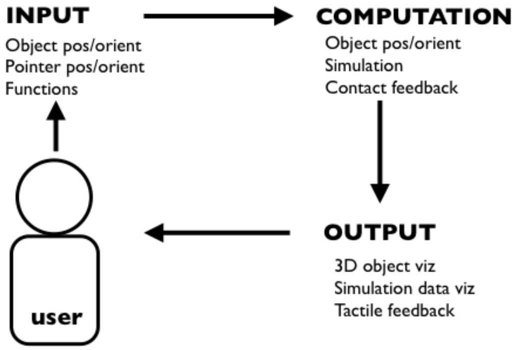

Figure 1. Interaction flow of the AR application.

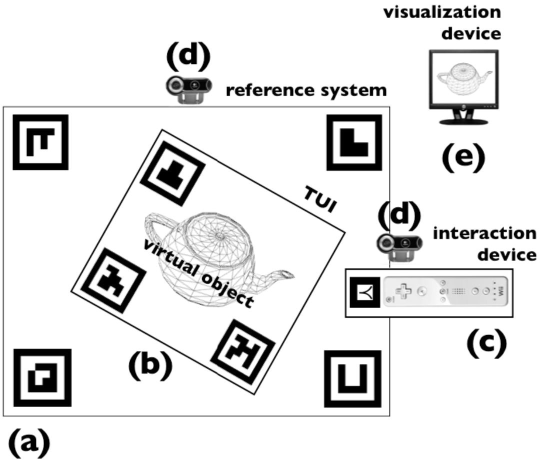

Figure 2. Set up of the AR application.

The "real" part of the application consists of the application context, which is augmented with virtual information that may be, for example, simulation data and user-object contact information (Figure 2). The application context is the following:

— a table, which is the user working space, Figure 2(a);
— a TUI implemented through a piece of paper glued on a rectangular wooden plate that the user can move and rotate in three dimensions; the piece of paper is augmented with markers for the interactive rendering of the virtual object (the teapot in the example), Figure 2(b);
— a 6 DOF input device, that is a marker-tracked WiiMote device that provides tactile feedback through vibration cues and some buttons used for activating the application functions, Figure 2(c);
— a display system used for visualizing the AR scene: a monitor or a handheld device, Figure 2(d).
— two video cameras and some markers used for implementing a marker-based tracking system. One of the cameras is used to track position and orientation of the TUI with respect to the reference system, while the other one is used to track the WiiMote, Figure 2(e).

The AR application is implemented by super imposing onto the real context the rendering of the virtual object, whose shape and position can be varied by using the TUI, and of the data resulting from the simulation. In addition, the simulation of contact with the virtual object (location and intensity) is rendered to the user through the tactile capabilities of the WiiMote device.

3.3. Application Architecture

During the implementation of our system we have focused on simplicity of the architecture and components and on their cost. Specifically, the application has been developed using low cost devices and technological solutions (video-cameras for marker-based tracking and WiiMote for direct interaction), and open-source libraries (CalculiX and OpenFOAM respectively for Structural FEA and CFD analyses, ARToolKit and VTK library).

The application architecture consists of the following components. The input information is directly inserted by the user through the WiiMote buttons or through cameras that capture the images of the real environment. These data are managed by the input event handler, which is implemented using the ARToolKit and Wiiyourself libraries. ARToolKit reads the position of the markers and returns the position and orientation of the camera that is looking at them. This module allows us to detect the position and orientation of the paper sheet and of the Wiimote device. The Wiiyourself lib returns an event when the "*A*" button is pushed.

The other system components consist of a geometry handler, a simulation module and a collision detection module. The input event handler generates the input data. All visual data are rendered in a VTK render-window that is superimposed onto the image acquired from the camera with the right perspective parameters given by ARToolKit. So we use ARToolKit only as a tracking system, and not for rendering also the virtual information. This is basically due to the fact that ARToolKit is not specifically developed for scientific visualization and so does not contain any complex dataset manager algorithm as VTK does, especially for CFD datasets. The feedback about the collision of the input device with the virtual objects in the scene is sent to the user through the visual/haptic channel, i.e. the user is able to see the device and the object colliding and feels a vibratory feedback as well.

3.4. Application in use

The application is used in the following way. The user moves the paper sheet for reorienting the virtual object in space, where the four markers fixed on the table represent the global reference system that is fixed. Then, the user uses the tracked interaction device for pointing at the virtual object and imposing pre processing conditions. For example, the user can set the loading conditions for structural analysis: when the WiiMote device reaches the surface of the object, it starts vibrating in order to inform the user of the contact and of the intensity of the force being applied. The user uses the WiiMote buttons for activating functions, in a way contextual to the type of analysis (for example, switch between flow properties settings). After setting the simulation parameters the user selects the WiiMote "*A*" button to run the simulation. Mesh properties as well as elements type and size are defined before the application starts and cannot be controlled and modified by the user.

After performing the simulation, the resulting data can be visualized through the Augmented Reality application by selecting the most appropriate visualization modality, which can be set by using the WiiMote device buttons or the application menu.

4. USERS' STUDY

Some aspects of the application have been evaluated through some preliminary tests. The aim of the tests was to check the intuitiveness of use of the interaction paradigm proposed, and the easiness in learning it. The experiments described hereafter concern the use of the application for structural analysis.

4.1. Description of the experiments

We have defined some users' tests on the basis of the state of the art methodologies for testing AR systems [12]. Figure 3 shows the application set up used for the experiment. The user sits in front of a screen where the virtual object is displayed, and handles the paper sheet with one hand, and

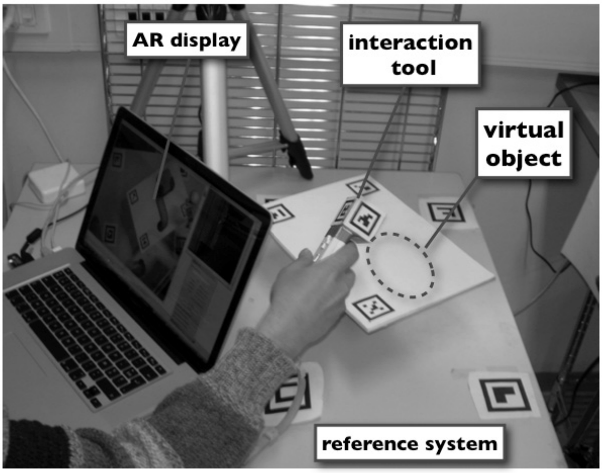

Figure 3. Users' study set up.

the WiiMote with the other hand. The products selected for the user study are objects with simple geometrical shapes, i.e. a plate with a hole in the middle and a U shape with square section.

Eight students (6 male and 2 female) of the master degree of mechanical engineering were selected, with some experience in structural analysis. Before the test they had to read a short document explaining the functionalities of the system and assist to a short demo. Then they could play with the system until they felt confident. We observed the testers during the experiments and took notes of their comments. Then, we asked the participants to accomplish the following tasks working on some simple objects, which they are used to study in the mechanical engineering courses and fill in some questionnaires:

Task 1

1. Put boundary conditions, i.e. fix one of the surfaces of the model.
2. Put a concentrated load in a specific point of the object surface.
3. Start the simulation.
4. Observe the results in AR switching from displacement to stress visualization, and describe the obtained effects.

Task 2

1. Put boundary conditions, i.e. fix one of the surfaces of the model.
2. Put a distributed load (direction and intensity) on the entire surface at the other extremity.
3. Start the simulation.
4. Observe the results in AR switching from displacement to stress/strain visualization, and describe the obtained effects.

Figure 4 shows two steps of use of the application: (a) setting concentrated load in a specific position of the surface, and (b) visualization of stress magnitude in the AR environment.

4.2. Analysis of Users' Study Results

The aim of the experiments were to prove the benefit of the proposed approach based on the "learning by doing" paradigm and on the use of more friendly interaction paradigms like AR visualization, direct pointing interaction and tactile feedback. In order to get a proper feedback about these issues, we have organized the questionnaires as follows: the first part includes questions about the testers'

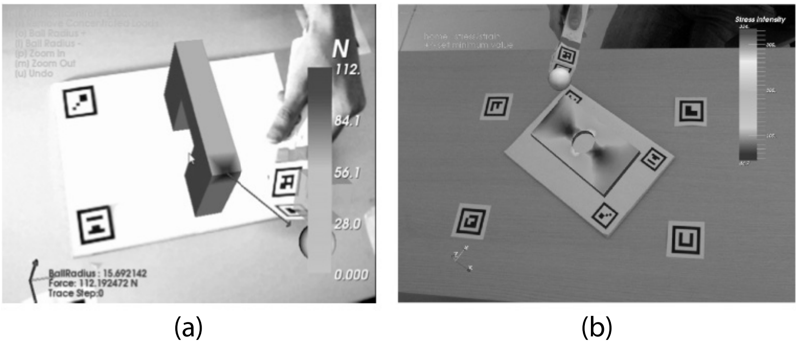

Figure 4. (a) Setting of concentrated load in a specific position of the surface; (b) visualization of stress magnitude in AR.

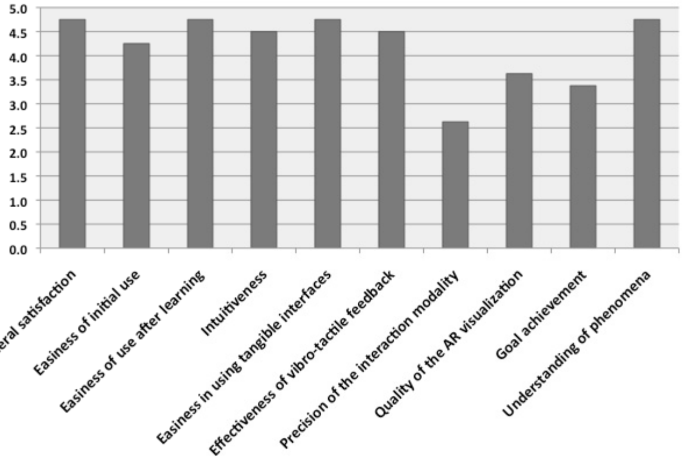

Figure 5. Results of the users' tests.

impressions (general satisfaction and appreciation of the proposed approach); the second part is oriented to understand the learning curve of the application (easiness of initial use, ability of use after learning); the third part is dedicated to test the specific functions of the interaction modality (for example, the easiness of using the TUI for orienting the object; the fourth part is devoted to the evaluation of the graphical user interface and of the AR visualization environment; and finally the last one is dedicated to check the effectiveness in terms of goal achievement (success in reaching the final goal required by the task, full comprehension of the simulated phenomena). The questionnaires were filled in after the completion of the tasks (on a scale 1-poor and 5-good), and additional comments have been added.

Figure 5 shows a chart reporting the results of the users' tests concerning the FEM analysis experiments. The general satisfaction in using the system is high, so it may suggest that with some adjustment and fine-tuning the system may be improved, also with the integration of additional functionalities. The testers actually reported a lack of precision in the definition of the parameters, but that was not considered a major issue in this phase. They found the quality of the displayed data better than the one provided by the usual structural analysis modules. Users encountered some difficulties, especially at the beginning of the test, to use efficiently the system, and as the learning curve demonstrates, after some trials, they were able to complete the task. We may suppose that the low value of goal achievement is probably connected to the learning curve. While it is interesting to note that most of the users have judged the whole system as a very useful tool to understand the phenomena by easily setting the initial parameters and immediately seeing the results, with the possibility of re-iterating the process several times.

5. CONCLUSIONS

The paper has presented a research work aiming at developing and testing an Augmented Reality environment integrated with real-time simulation algorithms in order to make the process of engineering analysis of product more natural and intuitive to use. The environment has been designed, implemented and tested with some students of the master degree in mechanical engineering of our University.

The major benefits of the application reported by the testers are the following:

— even if users are non-expert, they can perform simulations by setting the analysis conditions, verifying the results and testing the consequences of the changes of the experimental conditions. This may be done easily and quickly, several times. This is achieved through an action-reaction experimental use of the application. Users learn physical phenomena by doing and experimenting.
— the application implements a spatial and temporal co-location of the cause-effect of the phenomenon. The users do not need to wait long for the results of the computation of the effects of their actions before changing the simulation parameters and do not interfere with the experiment while changing the initial conditions.
— the visualization and interaction with the simulation results occurs in a more natural, realistic and direct way through 3D visualization, and through navigation of the object and simulation data.

For what concerns the future works, we are working on the improvement of the tracking of the interaction device by using the equipments mounted on the WiiMote control (infrared camera, accelerometer, gyroscope) in order to develop an auto-tracked device. In this way, we will not need to use the markers for tracking the interaction device; this would be a very useful feature in case the stereoscopic display system is a VST-HMD because the users do not need always to frame the interaction device during the execution of the tasks.

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