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Abstract

Virtual Reality (VR) allows engineers to naturally interact with three-dimensional digital models in a three-dimensional space. This provides a unique interface between users and computer models not found in traditional desktop environments. Common uses of virtual reality in product design include prototype evaluation, virtual assembly and visualization of engineering analysis results. This work described in this paper is based on a methodology for interactive design that uses virtual reality as an interface to product design and analysis. Computer analysis models coupled with fast reanalysis approximations and geometric models in a virtual environment are developed to facilitate shape design changes and updated analysis results in real-time. This combined design and analysis environment encourages the rapid investigation of many possible shape and design changes and how they affect the final product performance. The application developed to test this methodology is referred the Immersive Virtual Design Application (IVDA).

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HAPTIC FEEDBACK TO GUIDE INTERACTIVE PRODUCT DESIGN

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ABSTRACT

Virtual Reality (VR) allows engineers to naturally interact with three-dimensional digital models in a three-dimensional space. This provides a unique interface between users and computer models not found in traditional desktop environments. Common uses of virtual reality in product design include prototype evaluation, virtual assembly and visualization of engineering analysis results.

This work described in this paper is based on a methodology for interactive design that uses virtual reality as an interface to product design and analysis. Computer analysis models coupled with fast reanalysis approximations and geometric models in a virtual environment are developed to facilitate shape design changes and updated analysis results in real-time. This combined design and analysis environment encourages the rapid investigation of many possible shape and design changes and how they affect the final product performance. The application developed to test this methodology is referred the Immersive Virtual Design Application (IVDA).

INTRODUCTION

Immersion refers to a sense of "being there" that a user feels in the virtual world; the greater the level of immersion, the more real the virtual world appears and the more useful it becomes [1]. The level of immersion experienced in VR ranges from simple stereo vision on a desktop computer monitor to a multi-screen projection environment complete with active stereo vision, user position tracking and surround sound. The perceived level of immersion in a VR environment is directly related to the number of senses stimulated [2].

Unfortunately, many virtual reality systems and applications lack a key area of sensory stimulation:

some form of physical force or haptic feedback. The word haptics refers to the feeling of force, weight, roughness or other physical resistance felt by a user in a virtual environment. Adding haptic feedback to a virtual environment is expected to improve the level of immersion and thus the effectiveness of the application. Investigation of task times for virtual assembly indicates that adding force feedback increases the efficiency of the application [3]. Similarly, virtual prototyping, where virtual reality is used to evaluate part designs for criteria such as ease of use by human operators, also indicates the addition of haptic feedback significantly decreases task completion times [4].

The goal of this research is to integrate haptic feedback into the existing interactive design application, IVDA, in order to provide additional sensory feedback to the user. In order to achieve this goal, various ways to model the stress changes as haptic forces in order to convey information about the analysis back to the designer are explored.

BACKGROUND

The word "haptic" comes from the Greek *haptesthai*, meaning to touch or grab. The sense of touch has two components, tactile and kinesthetic. Tactile refers to the actual touching of a surface and the sensing of roughness, temperature, etc. Kinesthetic (dynamic) touch provides information about the physical properties of a whole object such as weight, size, and inertia. While the tactile sense depends on nerve endings in the body, the kinesthetic relies on the position of, and forces applied to, a user's hand and limbs [5].

There are a variety of fields that use haptic devices in situations such as design, simulation and operation. These range from more traditional areas such

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as surgery and assembly tasks to the more exotic exploration of multidimensional data sets [6].

In the early stages of product design, models, such as automotive body shapes, are often created using clay and then developed into a CAD model. A "digital clay" program would provide designers with the ability to sculpt clay models on the computer with a variety of tools [5]. SensAble's FreeForm modeling system, a digital clay sculpting software package for industrial designers, allows designers to sculpt virtual clay models to explore new product shape possibilities The IVDA expands upon the digital clay paradigm to include visual and haptic stress analysis feedback.

The purpose of IVDA is to allow a designer to interactively change the shape of a product within a virtual environment and examine the effect that shape change has on the stresses generated in the product. Stress analysis is an important engineering analysis tool used to identify areas of potential failure in a product. The IVDA method involves first creating a 3D CAD model and then performing a stress analysis of the part based on anticipated loading and boundary conditions. Once the initial stress analysis has been performed, the CAD model and the stress values are displayed in the virtual environment. The user interactively creates a bounding volume around the specific area of the part to indicate where shape changes will be allowed. By moving a control point on the bounding volume, the user changes the shape of the part and new stresses are calculated and displayed. With this application, the user can interactively explore several potential shape changes to the CAD geometry and examine the effects on the stresses in the geometry.

IVDA is a C++ program that is based on the VR Juggler software library developed at Iowa State University's Virtual Reality Applications Center. The use of this core software permits the application to run on a number of virtual reality devices including the Linux workstation cluster which drives the C6, a six-wall stereo projection immersive virtual reality environment [7].

Originally, IVDA relied on a simple linear Taylor series to interactively approximate the stresses. Pre-computed stress sensitivities were used to calculate the changes in stresses quickly as the user changed the shape of a part [8]. This process was limited to modeling small shape changes because of the linearity of the Taylor series stress approximations. The method also required the portion of the model marked for shape change to be identified beforehand, limiting a designer's ability to freely explore multiple shape changes.

The procedure was tested by applying these techniques to a practical engineering problem in a projection screen virtual environment. In particular, a tractor rear lift arm experienced excessively high stress levels while in use, but designers found it difficult to alter the shape without interfering with the rest of the complicated lift assembly. The virtual environment with real time stress approximations made it easy to explore the arm design and find a shape that lowered part stress to acceptable levels while avoiding interference with the assembly [9].

Further improvements were provided by Chipperfield, Yeh and Vance who implemented a mesh-free method and a faster stress reanalysis technique. A reproducing kernel mesh-free method with strain smoothing stabilization was implemented to compute the analysis results [10]. This helped reduce analysis errors arising from mesh distortion as the part shape was changed, and avoided the computationally expensive re-meshing process. The fast reanalysis uses a pre-conditioned conjugate gradient (PCG) method to rapidly resolve the system of equations arising from the mesh-free analysis. By using the factored stiffness matrix from the previous analysis, the PCG method can quickly solve the system for the deformed part shape [11]. The final result was a combination of Taylor series approximation for interactive analysis and PCG being used once the user stopped changing the part geometry.

Catmull-Clark subdivision volumes are used as the bounding volumes which define the area where shape changes are allowed [12]. By placing a series of control points in the 3D space surrounding the part, the designer creates a subdivided volume. The geometry and the analysis model are embedded into the volume. A designer in VR grabs and moves these bounding volume control points to change the underlying part shape.

To make the application more robust and applicable to a wider range of problems, Fischer and Vance integrated an external analysis program called Tahoe to perform the mesh-free analyses. Tahoe is a "research-oriented, open source platform for the development of numerical methods and material models" that places special emphasis on solving problems not treated well by standard continuum methods [13]. After testing to compare speed and accuracy with the already implemented custom mesh-free analysis, a Tahoe module was built for the IVDA that makes it the default analysis option. Figure 1 shows a user in the immersive virtual environment interacting with IVDA.

HAPTIC INTEGRATION

The goal of this research is to integrate a haptic device within the IVDA to provide additional sensory feedback to the user. The IVDA is a collection of C++ modules built upon VR Juggler. Separate modules deal with model data, file I/O, free-form deformation, mesh-free analysis, design sensitivity analysis, and Taylor series approximation.

Interfacing with the haptic computer was implemented by adding a specialized haptic controller module. This module communicates via TCP/IP data transfer with the haptic simulation computer. The haptic
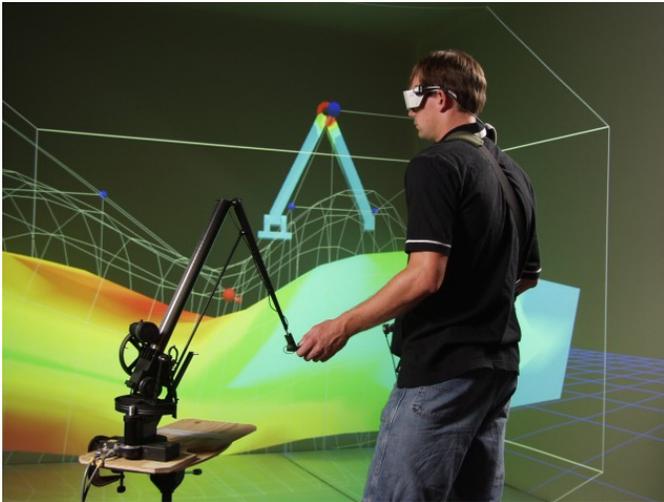
FIGURE 1. A user working with the Immersive Virtual Design Application

controller sets up the simulation by formatting and sending the locations of all control points from the model manager to the haptic computer. It then monitors for updated control point positions and passes those positions back to the core application to cause deformations. As the model shape changes, the haptic controller uses an algorithm to convert the changing stress state into a value to return to the haptic device for feedback.

The haptic controller is also an optional component. If no haptics are used, it does not need to be loaded or even compiled into the application. Figure 2 2shows a diagram of the IVDA application and the haptic controller module.
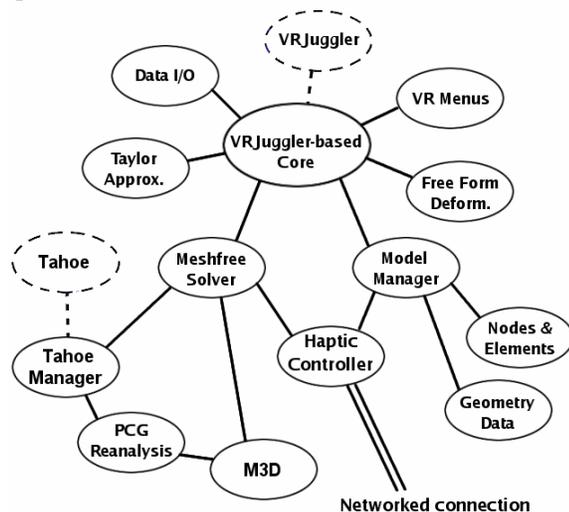

FIGURE 2. The haptic controller module in the IVDA

On the dedicated haptic computer, a program called the haptic server was written to control a haptic device and communicate with the IVDA simulation. This lets the haptic computer dedicate itself to driving the haptics and keeping update rates high. The haptic server was written using the OpenHaptics API to control the PHANTOM 3.0.

The haptic server is started before the IVDA simulation. It simply waits for a connection from a client, the haptic controller. Once connected it receives data and parses it for the PHANTOM, setting up control points and workspace bounds. When the haptic simulation starts, the haptic server relays control point translations to the IVDA and receives the user feedback information. This feedback is converted into a parameter meaningful to the PHANTOM.

Since the haptic server only updates the feedback when new information is received from the simulation, the PHANTOM servo loop may run as fast as possible. If the change in feedback levels is substantial, a linear interpolation may be used to smoothly apply the new forces to the haptic device, as in [14]. A graphical representation of the haptic server communicating with the IVDA's haptic controller and the PHANTOM appears in figure 3.
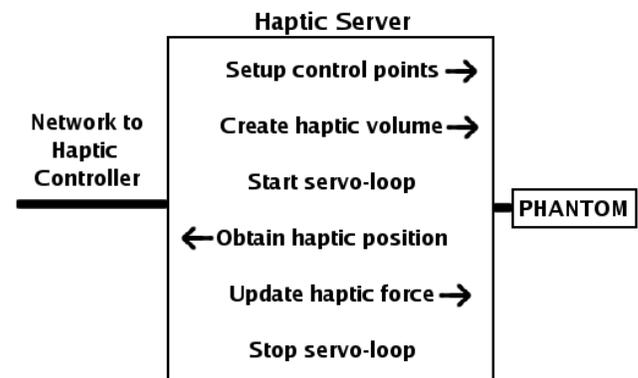

FIGURE 3. The haptic server

HAPTIC MODELING

The client/server framework allows the IVDA to work with a PHANTOM haptic device for feedback based on the changing stress state of the model being altered. Converting the model's changing stress pattern into a value for the haptic device is a highly empirical process. The goal is to produce a "feeling" for the user that conveys as much information about the stress state as possible.

Each mesh-free node (or "element") has a stress tensor associated with it, and a model typically has thousands of elements. The IVDA allows the user to select one of several different stress states to view, such as Von-Mises or maximum shear. Either state results in a scalar value of stress for each element. The challenge is to turn these individual element scalar values into a force value to send to the haptic device.

One approach is to model the force as the global mean of all stresses in the model as per equation 1.

$$\gamma = \sum_{i=1}^{N} \sigma_{VM}(i) \qquad (1)$$

Here γ is the force value to be sent to the haptic device, σ_{VM} is the Von-Mises stress per element, and N is the number of elements in the model. The disadvantage of this approach is that small changes or localized stress changes will be averaged out and not felt.

A second approach is to model the force according to the stress sensitivities. This should cause the areas being deformed to have a greater effect on the haptic feedback. This also removes the effect of stresses in areas not being deformed from the haptic feedback. Such a weighting is shown in equation 2.

$$\gamma = \sum_{i=1}^{N} \bar{h}(i)\sigma_{VM}(i) \qquad (2)$$

Here $\bar{h}$ is the average value of the stress sensitivities for each element, computed for the three coordinate directions x, y and z.

$$\bar{h} = \frac{h_x + h_y + h_z}{3} \qquad (3)$$

A third option is to provide a different level of haptic feedback for each coordinate direction. This might be accomplished in a manner similar equation 2, except it would require a weighted mean for each coordinate direction. This would also require returning a feedback vector to the haptic device instead of a scalar.

The last step before sending feedback to the device is to map it to some sort of range or scale. A value for haptic feedback needs to be seen within the context of a maximum and minimum to be meaningful. The minimum and maximum values used depend on the averaging method. For the first approach, the simple global average, the minimum and maximum stresses in the model are used. For the second and third approaches, the minimum and maximum of the stress times sensitivity value is used.

Finally, the feedback value(s) are mapped from 0 to 1 for convenience, where 0 is no feedback and 1 is the maximum feedback the haptic device is programmed to provide. Equation 4 presents this mapping, where γ_{haptic} ranges from 0 to 1 and γ_{min}, γ_{max} are the minimum and maximum as determined above.

$$\gamma_{haptic} = \frac{\gamma - \gamma_{min}}{\gamma_{max} - \gamma_{min}} \qquad (4)$$

Note that if we are using different feedback for each of the three coordinate directions, γ_{haptic} becomes a 3-dimensional vector instead of a scalar.

Once a value is generated to send to the haptic device, the second step is deciding just how to provide the haptic feedback on the device. The Open Haptics toolkit provides some examples of force feedback models that were considered. Consider the standard mass-spring-damper system, which appears in equation 5.

$$m\frac{\partial^2 x}{\partial t^2} + b\frac{\partial x}{\partial t} + kx = F \qquad (5)$$

Here m is the mass, b the damping constant, and k the spring constant. The feedback value could be used as input to any one of these parameters.

Practically, the choice of using the mass term, m, was discarded altogether. This parameter only affects the force through the acceleration. It gives the feeling of a weight being attached to the end of the device. This would not produce the desired result.

Adjusting the damping constant b generates a viscous, friction like effect to resist the motion of the user. As γ_{haptic} ranges from 0 to 1, b ranges from 0 to some maximum value determined by experiment with the device.

Using the stiffness constant k gives a direct spring force to resist motion based on the position of the device. Varying this value changes how difficult it is for the user to move the device, and hence deform the model. A suitable range for k is also determined by experiment with the device to avoid excessive force levels.

With no clear way to choose one force rendering method over another, both choices were implemented in a small pilot study designed to help determine how useful haptic feedback is to a user working with the IVDA. Details of the study are presented in the next section.

PILOT STUDY

A pilot study was performed to determine if a user of the IVDA perceives any benefit from force feedback tied to the stress levels in the deforming models and to determine if there is a user preference between spring force feedback or friction or damping feedback. This study was designed as a precursor to a larger scale user study on the effectiveness of the various stress-to-haptic feedback mapping techniques. For this pilot study, the simple stress averaging technique was used.

Setup

A total of eleven users participated in the study, each with varying levels of computer usage experience.

Video game use was questioned as well, since that was expected to have an impact on the user's willingness to experiment with the haptic device. Each participant was given a pre-study and a post-study questionnaire.

Users first were presented with instructions on the application then they completed the pre-study questionnaire and were placed in front of a sample version of the IVDA. This simplified version consisted of a simple beam model already loaded with a bounding volume defined, control points selected for deformation, and stress sensitivities computed. The tests were performed with a desktop VR setup instead of the intended immersive display for simplicity. Users wore active stereo-enabled glasses to provide stereo vision.

Participants were asked to deform the model with the haptic device using both spring and friction feedback. Users also had the chance to work with two different haptic devices, a small PHANTOM Omni and the larger PHANTOM 3.0. The post-study questionnaire was then completed.

Results

The first result of the study was that 9 out of 11 participants chose the spring force over the friction force as the force model for the haptic device. One user thought the force interfered with deforming the model, and another had no preference. Figure 4 shows these results.
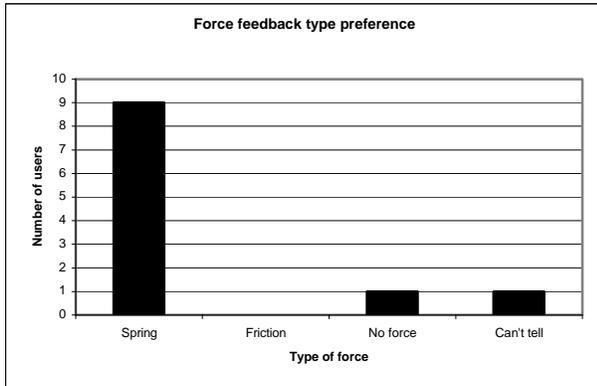

FIGURE 4. Comparing the different types of force feedback

The second result was that 7 out of 11 participants preferred the PHANTOM 3.0 over the Omni. This was expected because the 3.0 can produce larger forces and has a larger work area. Figure 5 shows these results.

This study was helpful in reinforcing the choice of the PHANTOM 3.0, and in deciding to use the spring force feedback model for further work with the IVDA.
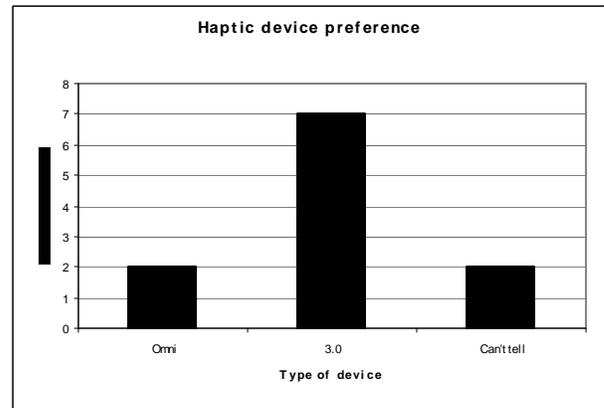

FIGURE 5. Comparing two different PHANTOM devices

CONCLUSIONS AND FUTURE WORK

Haptic feedback based on the changing stress levels in a deforming model was added to the Immersive Virtual Design Application. Haptic feedback was implemented with the existing IVDA and several mappings from model stress state to haptic feedback developed. A pilot study was performed to evaluate the different types of haptic feedback available to users of the IVDA to determine the most effective method. The study indicated that the spring model was most preferred and the PHANTOM 3.0 was preferred over the Omni.

Future work will consist of larger scale user study to compare a number of different stress mappings for haptic feedback. Combined with the PHANTOM 3.0 and spring force feedback, this future study should be used to determine the most useful way to couple haptic feedback with the immersive design application.

ACKNOWLEDGEMENTS

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