MIXED-REALITY ENVIRONMENT BASED ON HAPTICS AND INTERACTIVE SIMULATION FOR PRODUCT DESIGN REVIEW

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ABSTRACT

The aesthetic impact of a product is an important parameter that makes the difference among products technologically similar and with same functionalities. The shape, which is strictly connected to the aesthetic impact, has different meanings if seen from the design and the engineering point of view. This paper describes an environment based on an integration of Mixed-Reality technologies, haptic tools and interactive simulation systems, named PUODARSI whose aim is to support designers and engineers during the phase of design review of aesthetic products. The environment allows the designer to modify the object shape, through the use of haptic devices, and the engineer to run the fluid-dynamics simulation on the product shape. The paper describes the main problems faced in integrating tools, originally developed for different purposes and in particular issues concerning data exchange, and the choice of those algorithms that guarantees low computational time as required by the application.

Keywords: Mixed-Reality, haptic interfaces, fluid-dynamics analysis, design review.

1. INTRODUCTION

It is well known that the design review process is time consuming, requires the collaboration and synchronization of activities performed by the two type of experts having different competences and roles, and is performed using different tools and different product representations. For this reason, new tools supporting the process (Szalavari, Schmalstieg, Fuhrmann and Gervautz 1998, Dani and Gadh 1997, Jayaram, Connacher and Lyons 1997)

Conceptual design of shape of aesthetic products is usually performed by designers. Design review is mainly performed according to requests for changes coming from engineering studies. Sometimes, modifications to product shape are done on digital representations, some other times they are performed on physical prototypes of the product.

Analyses of the product design, such as structural FEM (Finite Element Method) or CFD (Computational Fluid Dynamic) analysis, are performed by engineers. According to the results, it is very common that the shape of the object requires to be modified. The modification impacts the aesthetic value of the product, and therefore the designer is asked to take part to that.

Recent techniques and technologies of virtual prototyping allow users to answer to the requirements of the traditional design, as well as to industrial design; they are based on the definition of a digital model of the product including geometrical, topological and functional information. The aim of virtual prototyping is to provide design and validation tools, which are easy to use, which improve the product quality, and at the same time reduce the need of building physical prototypes, which are expensive, require time, do not allow easy changes, configurations and variants, and often do not allow validation and checking iterations. The virtual prototype is used from the initial phases of the design process to perform analysis and validation through simulation, in order to reduce the number of physical prototypes needed, and concentrate their use just at the end of the design process (Ulrich and Eppinger 2004)

This paper describes the PUODARSI environment whose aim is to support designers and engineers during the phase of design review of aesthetic products. The environment is based on Augmented Reality and haptic tools for improving the design review process. The basic idea is having a unique environment that can be used in a collaborative way by designers and engineers, where the object shape can be visualized in a realistic modality and at the same time by the two users. The environment allows the designer to modify the object shape easily and intuitively, through the use of haptic devices, and the engineer to perform the analysis and simulation on the new shape. These activities are reiterated until a consensus about the aesthetic and technical aspects of the product is reached. The evaluation of the various solutions can be performed in comparative way, and decisions can be taken simultaneously and collaboratively by the two experts.

The paper presents the conceptual description of the environment, the hardware and software technologies selected, and its implementation. The research has been carried out in the context of the PUODARSI (Product User-Oriented Development based on Augmented Reality and interactive Simulation) project, funded by the Italian Ministry of University and Research.

2. SYSTEM CONCEPTION

The PUODARSI environment is an interactive system that allows users to visualize in 3D or in an Augmented Reality (AR) environment the geometrical model of a product, to perform fluid-dynamics tests in real-time and to modify the geometrical shape of the object.

The system is intended to be used for design review and analysis of a product whose geometrical representation is available. The geometrical representation of the product can be reconstructed from a real existing object by means of reverse engineering techniques, or it can be created using a CAD tool. The object model is imported within the PUODARSI environment and shown to users in stereoscopy or through the use of AR technologies.

Two are the users of the system: designer and analyst. The designer can evaluate the aesthetic shape of a product; the analyst is in charge of performing fluid-dynamics analysis (CFD) of the product model. The result of the CFD analysis is shown through the visualization of the velocity field of air around the object. The model and the analysis data may be visualized in a stereoscopic modality; alternatively, analysis data may be visualized onto the physical prototype of the product by using an AR technology (Figure 1).

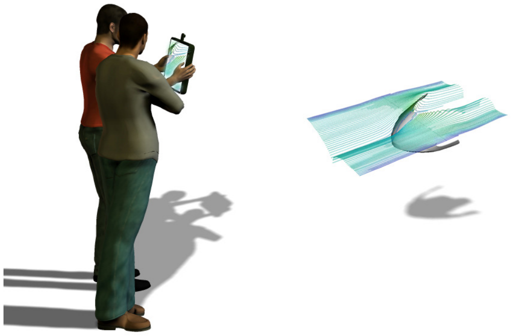

Figure 1: Conceptual image of the PUODARSI augmented reality environment where CFD analysis results can be seen super-imposed onto a physical prototype of the product.

The evaluation of fluid-dynamics characteristics of the model may reveal some problems (such as vortexes) that require a modification of the shape of the object in order to be fixed. Therefore, the analyst may decide to ask the designer to modify the shape providing specific information about the motivation and the area where to intervene. The designer can modify the shape of the product quickly, easily and intuitively using a haptic interface (Figure 2). The modification is performed on the basis of the requests made by the analyst, and also taking into account stylistic preferences.

Figure 2: Conceptual image of the PUODARSI haptic design environment.

The PUODARSI environment can be though of as a simulation of a wind tunnel where one can simulate the interaction of air with an object in a virtual environment, and where the object shape can be modified directly and interactively as if one were inside the wind tunnel, but without actually perturbing the phenomena.

2.1. Theoretical background

The architecture of the environment is demanding especially for what concerns the performances required (for example, interactive haptic rendering, real-time simulation), and the integrability of hardware and software components.

For what concerns the haptic rendering, we have focused on the so called ’haptic modeling’ that addresses the modeling of virtual shapes using haptic technologies. The novelty of these technologies is that they allow users to touch, feel, manipulate and model objects in a 3D virtual environment that is similar to a real natural setting. Several applications based on haptic modeling have been developed (Burdea 1999).

Some applications have been developed with the aim of providing haptic interaction with volume dataset, without actually providing realistic force feedback (Avila and Sobierajski 1996, Iwata and Noma 1993). Some sculpting systems have been developed based on haptic force associated with dynamic subdivision of solids, which give users the illusion of manipulating semi-elastic virtual clay (Celniker and Welsh 1992, Dachille, Qin and Kaufman 2001, Jagnow and Dorsey 2002).

Our research group has developed a system based on haptic technology for the generation and evaluation of digital shapes for aesthetic purposes. The system has been developed in the context of the T’nD project - a project partially funded by the European Union and has been described in several papers (Bordegoni and Cugini 2007). A subsequent project is ongoing for developing a system based on a new concept of haptic interface for shape evaluation and supporting a stereoscopic ergonomic setup. This new system is being developed within the framework of the European project SATIN - Sound And Tangible Interfaces for Novel product design (Bordegoni, Covarrubias and Cugini 2008).

Regarding Computational Fluid Dynamic (CFD) applications, they allow users to investigate the behaviour of the fluids in a fixed volume by numerical solving the differential equations of Navier-Stokes, through a discretization process that uses the finite volume method (standard approach), the finite elements or the finite differences (Ferziger and Peric 1999, Anderson 1995). A CFD simulation is divided into three distinguished phases: pre-processing, simulation and post-processing. The first step consists of the definition of the control volume, the generation of the mesh, and the physical parameters of the fluid. All these data are passed to a solver that computes the solution.

Scientific visualization algorithms are used to visualize the results of the simulation that generally consist of datasets. The visualization application aims at presenting to users the simulation data in intuitive and direct way. Some research works have tried to create real-time simulations of the fluid behaviours in virtual dynamic fields (Chen, Lobo and Moshell 1997).

3. OVERVIEW OF HARDWARE AND SOFTWARE

The hardware and software components of the system have been decided upon a thorough analysis of the state of the art in the reference domains: 3D visualization, haptic interfaces and interactive simulation. Some choices concerning hardware components have been done considering the various technologies already available at our labs; software components have been selected among available open source libraries.

For what concerns visualization systems, several VR technologies have been considered (Dai 1998), such as:

- the full immersion stereoscopic HMD, 5DT 3D HMD 800; the augmented see-through NOMAD HMD; the Nvisor ST see-through HMD.
- projection-based systems, such as a system developed within the context of the European project SATIN (Bordegoni, Covarrubias and Cugini 2008), and the SenseGraphics system.
- the wall display system CyViz.

For what concerns open source software libraries supporting stereoscopic visualization, we have considered VTK, openSceneGraph and OpenSG. These libraries have been considered mainly because of the possibility of integrating external libraries and of importing dataset generated by simulation environments. Particularly interesting for our aims is VTK, which is a scientific visualization library that manages CFD structured and unstructured grids. VTK library has been successfully integrated with the Augmented Reality library ARToolKit. This AR library is named VTK4AR. This library has been used for the visualization of CFD data in an AR environment as described in (Bruno, Caruso, Ferrise and Muzzupappa 2006).

For what regards the haptic system for haptic modeling, we have considered the following haptic devices at our disposal in our labs: the Phantom device by SensAble, the HapticMaster by MOOG-FCS and the Virtuose system by Haption.

The following open source software libraries supporting real-time haptic rendering have been considered: CHAI3D, H3D, HaptikLibrary, OpenHaptic, and osgHaptics.

It has been decided to use the Phantom device mainly because all the libraries for haptic rendering support these devices since are very common and diffused. For what concerns the software library, it has been decided to use a generic haptic library, such as the H3D library, instead of using a proprietary library like the Sensable OpenHaptic, because it allows us to develop the application for the Phantom device, but also to run it with other haptic devices also supported by the library.

According to the requirements of the PUODARSI framework some issues have to be considered for what concerns the selection of the interactive simulation environment. One issue is related to the possibility of creating pre-processing steps that can be run automatically; a second issue concerns the compatibility of simulation results with an external scientific visualization environment.

At the conclusion of the analysis of the hardware and software it has been demonstrated that the STL file format is a good compromise for exchanging tessellated geometrical data among different software. The mesh generation algorithm of our system is expected to receive an STL geometric file and to generate a mesh that is compatible with the CFD solver. The solver should compute the solution in real-time, and also should give output results that are easy to manage by using the selected scientific visualization environment (VTK environment in our case). The software libraries that satisfy these requirements are the following: Deal II, OpenFlower, Comsol Multiphysics and OpenFOAM. Deal II is too limited since it does not support unstructured grids and works only with QUAD (2D) and HEX (3D) elements. OpenFlower is also written in C++, supports unstructured grids and requires GMSH as mesh generation algorithm. Comsol Multiphysics allows users to run multi-physics simulation. Some tests have been carried out on these libraries to verify the feasibility of performing real-time simulations (Ambrogio, Bruno, Caruso, Muzzupappa and Bordegoni 2008). Finally, OpenFOAM runs exclusively on Linux/UNIX operating systems. It receives in input a mesh in the GMSH format thanks to the gmshToFoam function, and generates an output file that is compatible with VTK thanks to the foamToVTK function.

4. PUODARSI ENVIRONMENT

The definition of the PUODARSI architecture has been defined upon the selection of hardware and software components made on the basis of the state of the art analysis.

The PUODARSI environment consists of the following main three modules:

1. module for haptic modification of product shape,
2. module for 3D rendering of object shape and of scientific data, and
3. module for interactive CFD analysis.

For what concerns the haptic interface used for shape modification, it has been decided to use the SenseGraphics 3D-IW immersive workbench that consists of a Phantom haptic device integrated with a stereo visualization system including a CRT monitor, a semi-transparent mirror and some stereographic shutter glasses. This configuration allows a good collocation of the haptic and the stereoscopic visualization space, and is more ergonomic compared to HMDs that users are not keen on wearing for long periods.

Regarding the software architecture, the major aspect that has been considered for the selection of the software libraries is the support for data exchange from the haptic application to the CFD simulation environment, and from CFD module to the data visualization in a Virtual/Augmented Reality environment. The selection of the libraries also considers that the initial file received in input is a CAD geometric file in STL format. For what concerns the selection of the haptic library, the environment should include a library that allows us to modify a tessellated CAD model. Actually, for the purpose of the project, that is mainly performing a feasibility study, a simple single contact point deformation algorithm based on a three-dimensional Gaussian curve is enough.

The following sections present the system architecture, its modules and their implementation and integration.

4.1. System architecture

On the basis of the hardware selection and of the system requirements and software benchmarks, the following software libraries have been selected:

- H3D haptic library for deforming tessellated models;
- OpenFOAM library for performing real-time CFD analysis;
- VTK visualization library for scientific data visualization.
- ARToolKit as pattern-based tracking system for the visualization module.

H3D library has been considered the most appropriate solution for haptic rendering since it already includes some useful algorithms for implementing tessellated surfaces deformation. OpenFOAM library allows us to manage input files from CAD modeling software through the GMSH module, and to export the results to VTK. ARToolKit is suitable for supporting the implementation of an augmented reality application integrated with the VTK library.

The system architecture is based on the use of different computers for the visualization/haptic interaction and the simulation system; this choice has been made mainly because the OpenFOAM library works only on Linux operating systems.

The Visualization System has been defined as the main component that exchanges data with all the other components and serves as rendering engine all the system components, as shown in figure 3. The integration of software components is mainly based on data exchange. All data pass through the VTK library that exchanges geometrical models in STL format with the haptic system and with the CFD solver. Moreover, it receives results generated from the CFD analysis (exported in VTK format), processes these data and visualizes them.

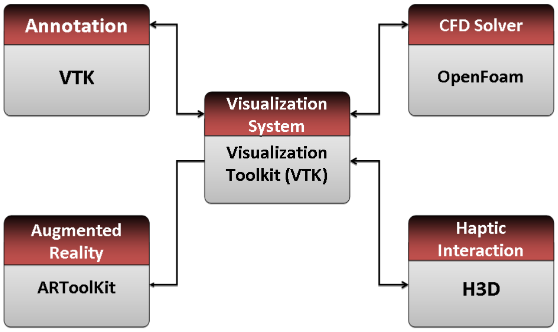

Figure 3: Software components of the PUODARSI environment.

4.2. System implementation

This section presents the PUODARSI environment, describing in details the implementation issues of its components and their connection.

4.2.1. CFD analysis module

The module for CFD analysis is implemented using the OpenFOAM library.

Since haptic libraries usually allow us to work easily especially with tessellated surfaces, it has been necessary to find a way to import tessellated geometries, create a control volume around these geometries to simulate the fluid volume and then generate a 3D mesh on the volume obtained by the subtraction of the volume of the model from the control volume.

For this purpose, the GMSH software library has been used for importing the geometry and generating the mesh. GMSH library works with .GEO files that are written in ASCII code using a very simple syntax; it can import STL files but does not work correctly when defining additional geometries (for example, the control volume). Therefore, a C++ routine for converting .STL files into .GEO file format has been implemented. The code works in such a way that, once the conversion is done, a control volume is created around the model.

After completing the definition of the geometry it is possible to generate the mesh (made of tetra elements) using the GMSH library. The output is a mesh file. Afterwards, the mesh can be converted in OpenFOAM format using the gmshToFOAM function included in the OpenFOAM package.

Once all information about the initial conditions is defined, the analysis can be launched using the solver routine icoFoam, a transient solver for incompressible, laminar flow of Newtonian fluids. Then the results are sent to the Visualization System that renders these data. The results of the analysis are transformed into a format that is compatible with VTK, using the function foamToVTK. This function creates a VTK file containing the definition of a VTK dataset and information about pressure and velocity for each vertex of the grid.

In our project VTK has been used to visualize geometry in STL format, and also the velocity field around the geometry that is obtained from the CFD analysis. By importing the dataset as a VTK unstructured grid it is possible to choose different modalities for representing a fluid flow field, such as stream tubes, stream ribbons, glyphs and so on, according to the preferences of the analyst that is performing the fluid-dynamics analysis. In the example reported in the following (Figures 4 and 5), we have decided to use streamlines to represent the velocity field. Streamlines are curves that are tangent to the velocity vector of the flow.

Figures 4 shows the results of the CFD analysis performed on an initial geometry of a windscreen; figure 5 shows the resulting analysis performed on the same object where the geometry has been modified using the haptic module.

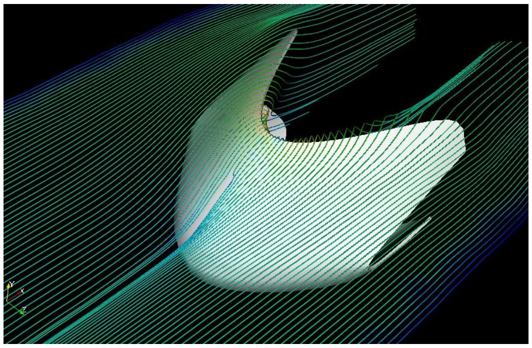

Figure 4: Fluid-dynamics analysis results performed on the initial geometry of a windscreen.

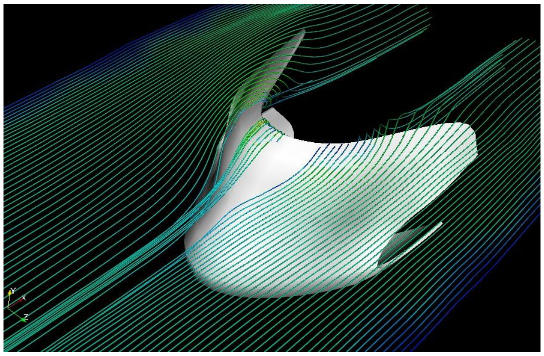

Figure 5: Fluid-dynamics analysis results performed on the modified geometry of a windscreen.

The VTK module is being integrated with the ARToolKit environment that supports Augmented Reality applications in a framework named VTK4AR (Bruno, Caruso, Ferrise and Muzzupappa 2006). This application allows users to see the object model and the analysis results in a stereoscopic environment.

4.2.2. Haptic shape modification module

The environment allows the designers to modify the object shape using a haptic module. The module is based on the SenseGraphics system consisting of an augmented reality visualization system, a haptic Phantom device and a 3D Connexion SpaceNavigator. The haptic shape modification module has been implemented using the H3D library.

H3D library works with geometries in the X3D format; since the model is initially available in STL format, it is necessary to create a converter from STL to X3D and from X3D to STL. The STL model is imported and transformed in X3D format, and then handles as a deformable shape (named DeformableShape). The haptic system deforms the geometry following a 3D Gaussian curve. The system provided users the possibility to change the width and the amplitude of the Gaussian function in order to define the area of influence of the deformation.

When the modification phase is finished, a new STL file representing the modified shape is generated; this model can be passed to the CFD module for running the analysis.

The model is visualized through the Visualization System. The system is based on the visual rendering library used by the haptic module that is VTK instead of H3D. The system includes a VTKrenderer function that has been specifically implemented for rendering 3D VTK objects (such as the output of the CFD module and annotations), X3D shapes and DeformableShapes. The visualization output is shown through the active stereoscopic window of the SenseGraphics system. Figure 6 shows a designer that is modifying the shape of a windscreen model using the haptic module.

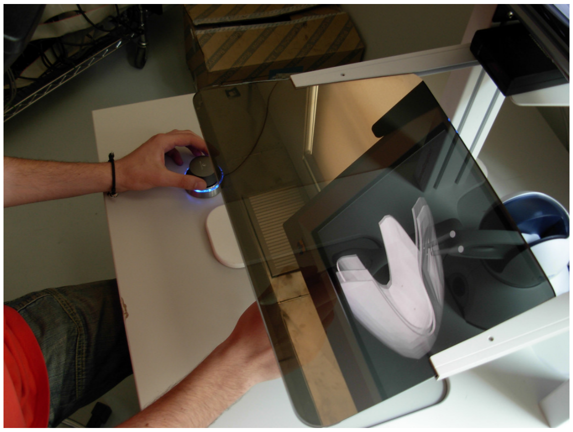

Figure 6: Use of haptic module based on the SenseGraphics system for the modification of the model of the windscreen.

4.2.3. Modules integration

Once the modules have been defined and implemented separately, it has been created a connection between them. The CFD application, using OpenFOAM library has been implemented on a machine running Linux operating system; the haptic module and the Visualization System, using H3D and VTK libraries, have been implemented on a machine running Windows operating system.

The haptic module and the Visualization System, and the CFD solver communicate through file exchange mode that is based on a Server/Client architecture using a TCP/IP connection (class ”socket”).

5. CONCLUSIONS

The paper has presented the preliminary results of the PUODARSI project aiming at developing an integrated environment for design reviews and real-time CFD analysis of aesthetic products. Some problems have been encountered during the selection of the components for the development of the environment, mainly from the software point of view, due to the exchange of information among the various components. Most of the components have been selected considering issue concerning integration among the various libraries rather than specific performances.

The system uses a STL file as an exchange shape data format, and the analysis and post-processing steps are completely independent from the modeling one. This will allow us in the future to develop the framework as an add-on for other modeling tools, such as the ones we are developing within the context of other two research projects, T’nD and SATIN projects, but also for the FreeForm system.

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