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Environment based on Augmented Reality 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. Product shape, which is strictly connected to the aesthetic impact, has different meanings if seen from the design and the engineering point of view. The conceptual design of shape of aesthetic products is usually performed by designers at the beginning of the product development cycle. Subsequent engineering design and studies, such as structural and fluid-dynamic analyses, lead to several design reviews where the original shape of the object is often modified. The design review process is time consuming, requires the collaboration and synchronization of activities performed by various experts having different competences and roles, and is performed using different tools and different product representations. Then, computer aided tools supporting conceptual design and analysis activities within the same environment are envisaged. The paper presents the conceptual description of an environment named PUODARSI that allows designers to modify the shape of a product and evaluate in real-time the impact of these changes on the results of the structural and fluid dynamic analyses in an Augmented Reality (AR) collaborative environment. Main problems in integrating tools developed for different purposes, such as, haptic interaction, FEM and CFD analyses, AR visualization concern the feasibility of the integration, the data exchange, and the choice of those algorithms that allow all that while guaranteeing low computational time. The paper describes the main issues related to the choice of hardware and software technologies, and the PUODARSI system implementation.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Scientific Visualization, Interaction Techniques; I.3.7 [Computer Graphics]: Virtual Reality

1. Introduction

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. 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 - designers and engineers- having different competences and roles, and is performed using different tools and different product representations. For this reason, new tools supporting the process and improving its performances are being studied [DG97], [SSFG98], [JCL97]. 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 [UE04]. Virtual prototyping and related techniques and technologies have become more and more a research topic of interest for the academic world as well as for the industrial one. Today, the virtual prototype allows designers to validate aesthetical, functional and ergonomics aspects. Some applications have reached satisfying results [SFH*00], [SSG*07], others need further analysis and development in order to be efficiently used in the industrial field.

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 some haptic devices, and the engineer to run the analysis and simulation on the new shape. This is reiterated up to reaching a consensus about the aesthetic and technical aspects. The evaluation of the various solutions can be performed in comparative way, and some annotations can also been attached to the object model and to the results of the simulations.

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 (http://www.kaemart.it/puodarsi).

2. Conceptual description of the environment

The conceptual image of the PUODARSI environment is shown in Figure 1. The environment consists of several hardware and software components supporting the requirements and operational modalities previously described. The environment would include an Augmented Reality stereoscopic visualization system allowing realistic rendering of the product model, a haptic interface for applying modifications to the model, and a real-time software application supporting functionalities for modifying the model and for performing analysis on that.

The architecture of the environment is complex, mainly because of the performances required (for example, interactive haptic rendering, real-time simulation), and the integrability of hardware and software components. The main issues addressed are the following:

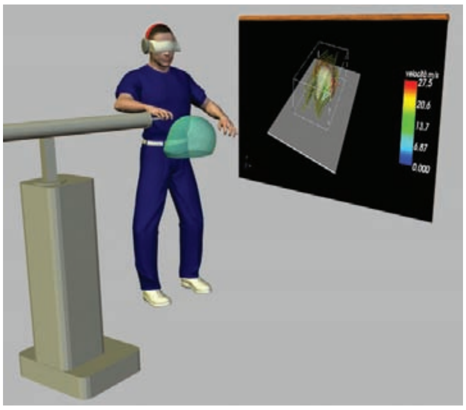

Figure 1: *Conceptual image of the PUODARSI environment.*

- model of object should be suitable for visualization, haptic rendering and also simulation. That means that the geometrical model should be accompanied by some other parameters concerning the physical properties of the object;
- haptic rendering requires real-time computation allowing interactive evaluation and modification of the shape;
- the analysis (FEM or CFD) should be run almost in real-time, in order to provide immediate feedback to the users for further design activities.

For what concerns the haptic rendering, we 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. Some applications have been developed with the aim of providing haptic interaction with volume dataset, without actually providing realistic force feedback [AS96], [IN93]. Solutions based on geometric and volumetric modeling for enabling local deformation are presented in [FCG02]. More general models support global deformations, and mimic the global and local effects of plasticity, mass preservation and surface tension that are typical of clay material [DC04]. Some other applications are more related to physics-based shape modeling. An overview of physics-based deformable models is provided in [NMK*05]. 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 [CW92], [DQK01], [JD02]. In order for the haptic device to exert appropriate forces in response to users' actions the virtual object and its properties are simulated by means of a physics-based model. Various physics-based modeling techniques have been developed. Terzopoulous and Fleisher provide a basis for physics-based design supporting simple interactive sculpting using viscoelastic and plastic models [TF88]. Celniker and Gossard developed a prototype system for interactive design based on finite-element optimization of energy functionals [CG91]. Celniker and Welch investigated deformable B-splines with linear constraints [CW92]. Other methods implement dynamic sculpting with haptics spline models controlled by physical laws subject to various constraints [DQK01]. Interactive sculpting framework based on subdivision solids and physics-based modeling has been proposed in [MQW01]. Most of the above-mentioned systems are based on the use of the point-based Phantom stylus by SenSable Technologies Inc. for interacting with the virtual clay. The only physically based shape modeling system commercially available is FreeForm by SenSable Technologies Inc., which is based on the Phantom haptic device (http://www.sensable.com/freeform/freeform.html). Users work directly with the digital clay using the Phantom stylus as a modeling tool. Hardness and surface smoothness of the clay can be varied, and different modeling tools can be selected. The material can be removed using some carving operators, but the user can also work from inside out pulling and deforming the shape. A study worth mentioning in the context of shape generation based on haptics concerns the Prop device that is a physical piece of material manipulated and deformed by users. The deformation is acquired by a motion capture system and reported into the corresponding digital model [SBS06]. Finally, 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 (http://www.kaemart.it/touch-and-design) and has been described in several papers [BC07]. A following 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 (http://www.satin-project.eu) [BCC08].

Regarding the interactive real-time simulation we have focused our initial research mainly on CFD analysis, FEM structural analysis data are simpler to manage than the CFD ones. Computational Fluid Dynamic applications 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 [FP99], [And95]. 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. 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 [CLM97].

3. State of Art of hardware and software

The definition of the hardware and software components of the system has been decided upon a thorough analysis of the state of the art in the reference domains: visualization systems, haptic interfaces and interactive simulation systems. Some choices concerning hardware components have been done considering the various technologies already available at our labs.

For what concerns visualization systems, several AR/VR technology has been considered, such as:

- a full immersion HMD (and specifically the 5DT 3D HMD 800 stereo: http://www.5dt.com), an augmented see-though HMD (and specifically the NOMAD HMD: http://www.nomad.com), and a prototype of a stereo video see-through HMD developed at the Department of Mechanical Engineering of Politecnico di Milano.
- projection-based systems, such as a system developed within the context of the European project SATIN [BCC08], and the SenseGraphics system (http://www.sensegraphcs.com)
- Wall display (CyViz: http://www.cyviz.com).

For what concerns libraries supporting stereoscopic visualization, we have analysed opensource libraries. Among those, we have considered VTK (http://www.vtk.org) openSceneGraph (http://www.openscenegraph.org/) and OpenSG (http://opensg.vrsource.org/trac). Particularly interesting is VTK, which is a scientific visualization library that manages CFD structured and unstructured grids and has been already successfully integrated with the AR library ARToolKit (http://www.hitl.washington.edu/artoolkit/), and that has been also tested for the visualization of CFD data in Augmented Reality [BCFM06]. VTK is also available in a different version with a graphical interface that is named Paraview (http://www.paraview.org) that allows us to manage the same data of VTK without the need of using a programming language and is very useful to use instead of VTK in this first development stage. These libraries have been considered mainly because of the possibility of integrating external libraries and of importing dataset generated by simulation environments.

So regarding the haptic system for haptic modelling, we have considered the various technologies at our disposal in our labs and evaluated the benefits and disadvantages in using one technology compared to other ones. Specifically, we have considered the following haptic devices: Phantom by Sensable (http://www.sensable.com), HapticMaster by MOOG-FCS (http://www.moog-fcs.com) and Virtuose system by Haption (http://www.haption.com). Open source software libraries supporting real-time haptic rendering have been considered: CHAI3D (http://www.chai3d.org), H3D (http://www.h3d.org), HaptikLibrary (http://www.haptik-library.org), OpenHaptic (http://www.sensable.com), and osgHaptics (http://www.vrlab.umu.se/research/osgHaptics). Some tests have been performed using these libraries, mainly with the aim of evaluating the possibility of integrating them with the other software components of the system. Following these benchmarking activities it has been decided to use the Phantom devices mainly because all the libraries for haptic rendering support these devices, due to the fact that are very common and diffused devices. For what concerns the software library, it has been decided to use a generic haptic library, such as H3D library, instead of using a proprietary library as the Sensable OpenHaptic is, because it allows us to develop the application for the Phantom devices but also to run it with other haptic devices 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 simulation environment. The first issue is related to the possibility of creating pre-processing steps that can be run automatically; then the simulation results should be compatible with an external scientific visualization environment.

The mesh generation algorithm must receive an STL geometric file (the STL file format is a good compromise for exchanging tessellated geometrical data among different software) , and generate a mesh compatible with the 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. The software libraries that satisfy these requirements are the following: Deal II, OpenFlower, Comsol Multiphysics and OpenFOAM. Deal II (http://www.dealii.org) is an Open Source library written in C++ that is fast enough but is too limited since it does not support unstructured grids, and works only with QUAD (2D) and HEX (3D) elements. OpenFlower (http://openflower.sourceforge.net) is also written in C++, supports non structured grids and requires GMSH (http://www.geuz.org/gmsh) as mesh generation algorithm. Comsol (http://www.comsol.com/) allows users to run multiphysics simulation; it is not only a solver but it also supports the pre and post processing steps. Some tests have been carried out on these libraries to verify the feasibility of a real time simulation [ABC*08]. Finally, OpenFOAM (http://www.opencfd.co.uk/openfoam) is written in C++ and runs only under Linux/UNIX operating systems, receives as input GMSH files thanks to the gmshToFoam function and the more important thing is that it generates as output files compatible with VTK/Paraview thanks to the foamToVTK function.

4. PUODARSI environment development

The analysis of the state of the art has led us to the definition of hardware and software architecture of the PUODARSI environment. For what concerns haptic tools used for shape modification, the hardware we have decided to use is the SenseGraphics 3D-IW immersive workbench (http://www.sensegraphics.com/) that includes a Phantom haptic device integrated with a stereo visualization system composed by a CRT monitor, a semitransparent mirror and the Stereographics shutter glasses.

For the analysis that runs only on a Linux pc, a multi core processor that allows to reduce the time needed for calculation has been used. Regarding the software architecture, the most important aspect that has been considered in the selection of the software is the support in data exchange from the haptic application to the CFD simulation environment, and from the CFD to the visualization in an Augmented Reality environment, also taking into account that the initial file received in input by the environment is a CAD geometric file in STL format. Regarding the selection of the haptic library, the PUODARSI environment should use a library that allows us to modify a tessellated CAD model. Actually, for the purpose of the project a simple single contact point deformation algorithm based on a three-dimensional Gaussian curve is enough. Therefore, H3D library has been considered the more appropriate solution since it already includes some useful algorithms for implementing tessellated surfaces deformation. Finally, concerning the CFD simulation software, OpenFoam library allows us to manage input files from CAD modelling software through GMSH, and exporting the results to VTK.

4.1. System architecture

The results of the state of the art analysis and of benchmarks and tests of computational fluid-dynamic algorithms, scientific visualization and haptic rendering libraries, have led us to the definition of the architecture of the system with the following software libraries:

- H3D as haptic library
- OpenFOAM library for CFD analysis
- VTK as visualization library

PUODARSI environment is an interactive system that allows users to 1) visualize the geometry model of a product, 2) visualize the velocity field of air around it, 3) modify the geometry and see how the modification influences aerodynamic characteristics of the model. In order to perform that, it has been necessary to do the following:

1. study separately the three modules and define stand-alone environments

2. define a connection between the environments to have them working together

We have decided to use different computers for the visualization/haptic interaction and the simulation system, mainly because OpenFOAM library works only with Linux operating systems, and also because it is useful to use an independent and more powerful hardware for numerical analysis, that certainly needs more computational resources than the other system components. The integration of software components is mainly based on data exchange. The visualization module has been defined as the main component that exchanges data with all the other components, as shown in Figure 2.

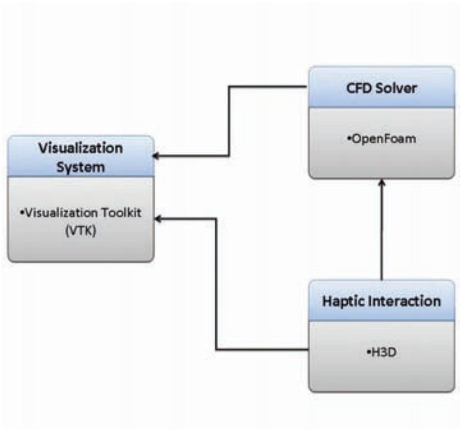

Figure 2: *Software architecture of the PUODARSI environment.*

Therefore, all data pass through VTK library that exchanges geometrical models in the 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.

4.2. Implementation

This section describes the PUODARSI environment, its components and the connection between them.

4.2.1. Haptic surface modification

The haptic modification of surfaces is based on the use of a Phantom device connected with H3D library. H3D library is an open-source haptic library written in C++ that works with geometries in the X3D format; so it is necessary to create a converter from STL to X3D and from X3D to STL. In this way the software can read STL models, apply haptic interaction and save the modified geometries again in STL format. The model is imported in STL format and transformed in X3D format, then defined as DeformableShape. Thanks to a function called CoordinateDeformer, applied to the geometry with a plasticity that initially is defined as default at a fixed value but can change dynamically when the application is running according to the choice of the modeler, the geometry can be modified, and then when the modification phase is finished, the new STL file is generated and the CFD analysis starts. Regarding the modification tool, the haptic system deforms the geometry following a 3D Gaussian curve, thanks to the H3D function GaussianFunction, with a fixed width at the beginning. The width defines the area of influence of the haptic interaction, around the contact point. The modeler can choose the plasticity of the model, as said before but also the value of the width, so the area of influence of the modification, both when the application is running.

4.2.2. CFD Analysis

The module for CFD analysis is implemented using OpenFOAM library. OpenFOAM library can be described as a collection of several different solvers for continuum mechanics problems, including computational fluid dynamic problems. All solvers and functions are open source and written in C++. The definition of the geometry has been studied considering the possibility to apply haptic modifications to the model. Since usually haptic libraries allow users 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. The software GMSH has been used to import the geometry and generate the mesh. GMSH works with .GEO files that are written in ASCII code with a very simple syntax; it can import STL files but does not work correctly when defining additional geometries (control volume). Therefore, a C++ code 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. An example of a conversion from STL to GEO file formats is shown in Figure 3.

After completing the definition of the geometry it is possible to generate the mesh (made of tetra elements) using Gmsh in batch mode, simply executing the following command line:

```
gmsh -3 filename.geo
```

where filename.geo is the file obtained from the conversion from STL. The output is a mesh file: filename.msh. Afterwards, the mesh can be converted in OpenFOAM format using a function included in the OpenFOAM package: gmshToFOAM. OpenFOAM requires that a folder of the analysis is defined, with ASCII files containing information like initial conditions, initial and final time, viscosity of the flow etc. Those files are independent from the geometry to analyze, and so they have to be defined only at the beginning of the process. Once all information is defined, the analy-

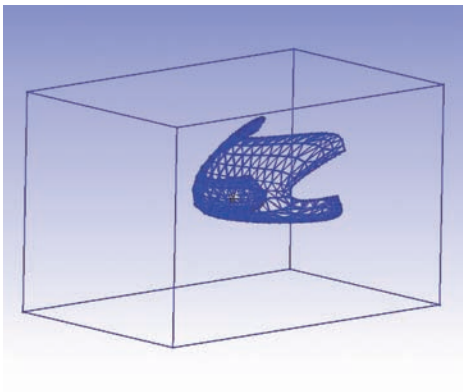

Figure 3: *Model Converted from STL to 3D Mesh.*

sis can be launched using the solver icoFoam, a transient solver for incompressible, laminar flow of Newtonian fluids. Once the analysis is complete, it is possible to convert post processing data in a format 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.

4.2.3. Post Processing and annotation - The Visualization Toolkit

Visualization Toolkit is an open source library for Scientific Visualization written in C++. This library allows developers to easily visualize data obtained from scientific simulations; in this project VTK has been used to visualize geometry in STL format and the velocity field around this geometry that is obtained from CFD analysis. In particular, we have decided to use Streamlines to represent the velocity field. Streamlines are curves that are tangent to the velocity vector of the flow. The class vtkStreamLines automatically generates streamlines from a dataset containing velocity components on the vertices of the elements that compose the dataset. By importing the dataset as a VTK unstructured grid it is possible to choose different modalities of representing a fluid flow field, such as stream tubes, stream ribbons, glyphs and so on, according to the preferences of the engineer that is analyzing the results. He will also be able to apply some notes on the model that he is visualizing to communicate to the modeler some information, always using VTK. Figures 4 and 5 show the initial and the modified geometry and the CFD analysis results.

Once the separated modules have been defined, it has been created a connection between the environments thanks to the class "socket" that has been used to create a Server/Client system between the visualization environment and the CFD solver. Figure 6 shows how the connection has been defined.

The haptic library (H3D) and the CFD environment communicate through a simple file exchange.

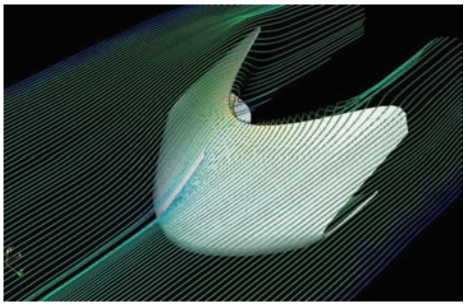

Figure 4: *Initial geometry.*

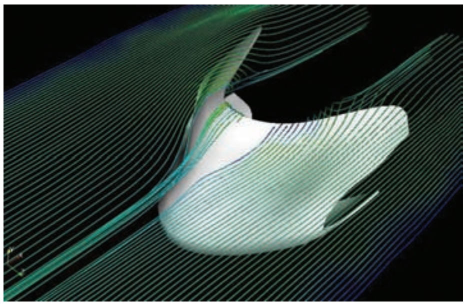

Figure 5: *Modified geometry.*

5. Conclusions

The paper has presented the preliminary results if 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. The paper has described the available hardware and software components to use for the system development and the ones selected including motivations. Most of the compo-

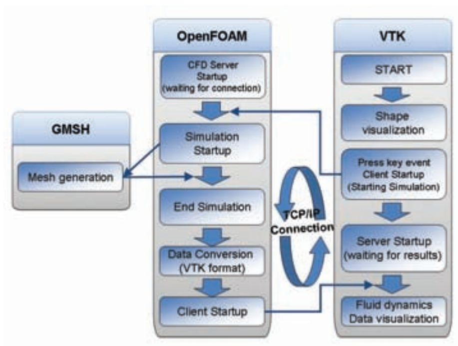

Figure 6: *Description of socket connection.*

nents have been selected considering issue concerning integration among the various libraries rather then specific performances. The environment allows designers and engineers to modify the object shape in a punctual way, and to choose some parameters concerning the response of the material, or the area of influence of the modification, but still does not take into accounts problems connected with the continuity of the curve or the curvature typical of the surface modeling. The developed environment takes as input STL files, and the analysis and post-processing steps are completely independent from the modeling one, except for the input file. This will allow us in the future to develop the framework as an add-on for other modeling tools, such as the T'nD and the SATIN systems, but also Freeform, and the specific one developed for the PUODARSI environment that will use in the future VTK as visualization rendering software so that to allow the designer to receive comments from the analysis through the annotation system developed using VTK.

6. Acknowledgement

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