7 AN INTEGRATED ENVIRONMENT FOR SHAPE MODELING AND FLUID-DYNAMIC ANALYSIS

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In order to improve the performances of the overall design process of products, it would be beneficial the availability of computer-aided tools supporting conceptual design and simulation activities within an integrated environment based on a multi-disciplinary model paradigm and supporting more intuitive interaction modalities. The paper presents an integrated environment named PUODARSI that allows designers to modify the shape of a product through haptic interaction and to test the impact of these changes from a fluid-dynamic viewpoint. The environment includes modelling and analysis tools that are integrated by means of shared data models.

Keywords: Product Design, Design Collaboration, Shape Modeling, Fluid-Dynamic Analysis.

1. INTRODUCTION

The product design and engineering process comprises various activities that start from market analysis and concludes with product distribution and maintenance.[1] Improvements in the product development process have been pushed by factors such as design costs, performances required and reduced time-to-market. In the last decades most achieved improvements concern methodologies, tools, and technologies for supporting the various phases of the product development. Activities like product definition and conceptualization, aesthetic design, detailed design, testing and simulation, and manufacturing are today performed in a digital context. Companies often operate in a context of Virtual Enterprise where the activities are actually distributed in the various offices, or are sub-contracted to other companies in a dynamic way. In addition, concurrent engineering paradigms are being implemented by these companies and mainly consist of restructuring the organizations of design and engineering activities through a parallel and close collaboration among the various deputy offices and human resources. Also product testing is today performed in digital environments and aims at checking whether product requirements are met by designs, and at studying design alternatives in case targets are not met.

Recently, we are facing a trend where traditional computer-aided tools (CAD/CAE/CAM) are being included into a more comprehensive environment, where aesthetic, ergonomic and also structural characteristics can be analysed minimizing the need of physical prototypes; this is named Virtual Prototyping.[2] These tools are used by different users in different phases of the product design, but they are not integrated and the exchange of data models and results is still a major issue.

We concentrate on two major aspects that we consider particularly important in this context:

- *new interaction modalities* of design and engineering tools that better meet users' expectation. Examples are haptic interfaces that allow physical interaction with the virtual products,[3] and mixed and augmented reality systems that allow mixing virtual and physical objects within the users' working space.[4]

– *multi-disciplinary model paradigms* supporting effective collaborative design-review.[5] This requires the study of tool-set that can be used by several users — possibly distributed — to test various product aspects, operating on different views and representations of the same product model. In addition, there should be a close loop between the re-design and testing activities, that should be possible to perform interactively and in a unique environment.

The paper analyses issues related to the integration of tools in the context of virtual design. In particular, we describe an environment we have developed that integrates a shape modelling tool with a fluid-dynamic analysis tool that has been implemented through data model sharing, and a case study showing its functionality. The research has been carried out in the context of the PUODARSI (Product User-Oriented Development based on Augmented Reality and interactive Simulation) project (http://www.kaemart.it/puodarsi).

2. CONCEPTUAL DESCRIPTION OF THE ENVIRONMENT

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 assessment and analysis of a product whose geometrical representation is available. The geometrical representation of the product can be reconstructed from a real 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.

The system provides two types of users: 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.

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. The modification is performed on the basis of the requests made by the analyst, and also taking into account stylistic preferences.

The users can also insert annotations that may be related to the object geometry or to the analysis data. For example, the analyst can attach an annotation such as “vortex generates in this area, surface should be made more flat” to an area of the object surface.

2.1. Case Study

In order to proof the concept we have identified a case study, which consists of the design review of a motorbike windscreen. In a first scenario (Scenario 1) the geometry of the product has been developed using a CAD tool. In a second scenario (Scenario 2), the product is physically available and its geometrical representation has been created using a reverse engineering process. The geometrical representation of the object can be visualized within the environment. The designer can evaluate the shape of the windscreen; the analyst may decide to run the fluid-dynamics analysis of the shape. Once the simulation computation is finished, the system graphically visualizes the velocity field of air around the object. The visualization can be stereoscopic, or in case a physical prototype of the windscreen is available (Scenario 2), the velocity field of air is visualized on top of the physical prototype through the use of an augmented reality system. The evaluation of fluid-dynamic 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. The designer intervenes for applying modifications to the shape through the use of the haptic interface.

The PUODARSI environment consists of several hardware and software components supporting the activities and operational modalities described above. The environment includes a 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 for fluid-dynamic analysis of the model.

3. THE INTEGRATED VIRTUAL REALITY ENVIRONMENT

The PUODARSI environment is an interactive system that allows users to visualize realistically the geometry model of a product, visualize the velocity field of air around it, modify the geometry in an intuitive way (by using haptic interfaces) and see how the modification influences fluid-dynamics characteristics of the model. The following sections describe the modeling methods for shape modeling, analysis and visualization and for haptic rendering, and the state of the art concerning Virtual Reality technology[6] and open source software used for the system implementation.

3.1. Modeling Methods

The architecture of the environment needs to be defined taking into account some requirements, like performances (for example, interactive haptic rendering, real-time simulation), and integrability of hardware and software components. The main issues addressed are the following:

- model of object should be suitable for visualization, haptic rendering and also simulation. This 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 modification of geometry of the object;
- the fluid dynamic analysis should provide real-time responses in order to give immediate feedback to the users.

For what concerns the haptic rendering, we have focused on the so called 'haptic modelling' that addresses the modelling 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 modelling have been developed; most of them are based on the use of the point-based Phantom stylus by SensAble Technologies Inc. for interacting with the virtual model. 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.[7–9] 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 modelling techniques have been developed.[7–10] The only physically based shape modelling 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 modelling tool. Hardness and surface smoothness of the clay can be varied, and different modelling 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.

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.touch-and-design.eu) and has been described in several papers.[3] 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).[11]

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.[12,13] 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.[14]

3.2. System Architecture

The PUODARSI environment consists of the following three main 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 (http://www.sensegraphcs.com) that consists of a Phantom haptic device (http://www.sensable.com) 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 Head Mounted Displays 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. Some tests have been carried out on commercial software and open source libraries in order to verify the feasibility of performing real-time simulations;[15,16] it has been necessary to perform tests for many different solutions before finding out the most useful one for the aim of the project. In the following we describe the libraries that have been selected for the implementation of the various modules and how those modules have been integrated into the environment. The selection of the libraries also considers the fact that the initial file received in input is a CAD geometric file in STL format, because haptic libraries usually allow us to modify only tessellated CAD models. Moreover, the selection of the STL format will not be a limit for the application, considering that all CAD tools allow users to export geometries in a tessellated format. 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.

3.3. Software and Hardware Components

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

– *H3D haptic library* (http://www.h3d.org) for deforming tessellated models;
– *OpenFOAM library* for performing real-time CFD analysis (http://www.opencfd.co.uk/openfoam);
– *VTK visualization library* (http://www.vtk.org) for scientific data visualization.
– *ARToolKit* as pattern-based tracking system for the visualization module.

The 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 modelling software through the

GMSH module, and to export the results to VTK. The Augmented Reality library ARToolKit (http://www.hitl.washington.edu/artoolkit/). is suitable for supporting the implementation of an augmented reality application integrated with the VTK library.

In order to satisfy the system requirements, we have first studied separately the four modules and defined stand-alone components, and then we have implemented the connections among the components. 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, 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. Since the environment supports collaborative activities of users, its graphic interface has been created using cross-platform libraries, with the possibility to start the simulations directly from these interfaces and using the analysis environment in batch mode.

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 1. 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.

4. SYSTEM IMPLEMENTATION

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

4.1. CFD Analysis Module

The module for CFD analysis is implemented using the open source OpenFOAM library, which is a collection of several different solvers for continuum mechanics problems, including computational fluid dynamic problems.

The type of representation of the geometry of the object that one intends to analyze with the CFD module has been studied considering the possibility of easily exchanging this geometry with the haptic module used for applying modifications. 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 and can import STL files but does not work correctly

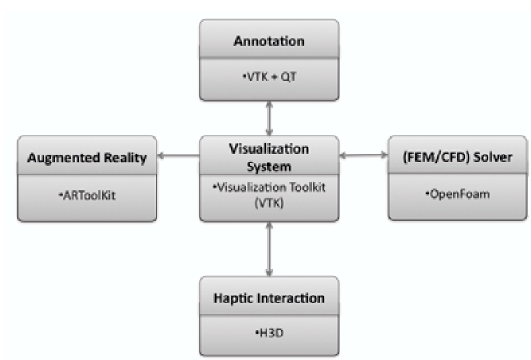

Figure 1. Software components of the PUODARSI environment.

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 GMSH library in batch mode.

Once all information is defined, the analysis can be launched. Once the analysis is complete, 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. The Visualization Toolkit — VTK is an open source library for Scientific Visualization that allows developers to easily visualize data obtained from scientific simulations. 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.

Figure 2 shows the results of the CFD analysis performed on an initial geometry of a windscreen, and on the same object where the geometry has been modified using the haptic module. Streamlines are used to represent the velocity field.

The VTK module is being integrated with the ARToolKit environment that supports Virtual/Augmented Reality applications in a framework named VTK4AR.[17] This application allows users to see the object model and the analysis results in a stereoscopic environment. The future release of the system will also support Scenario 2 described in Section 2.1, allowing users to see the analysis results (velocity fields) superimposed on a physical model of the windscreen through the use of the augmented reality environment.

4.2. 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 (http://3dconnexion.com). The user sees a 3D representation of the virtual object, interacts haptically with it through the Phantom device and uses the 3D mouse for easily positioning and rotating the model of the object in space. The user handles the Phantom stylus: he moves it over the surface for evaluating the curvature; the surface modification modality is activated when the button located on the stylus is pushed. The haptic shape modification module has been implemented using the H3D library, which is an open source haptic library that works with geometries in the X3D format. Since the model is initially available in STL format, it has been necessary to write a converter from STL to X3D and from X3D to STL. We have implemented a function that handles shape modification and manages plasticity values that are initially defined at a fixed default value, but that can be changed dynamically by the designer during the shape modification task. The haptic system deforms the geometry following a 3D Gaussian curve. The system provides 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 visualization output is

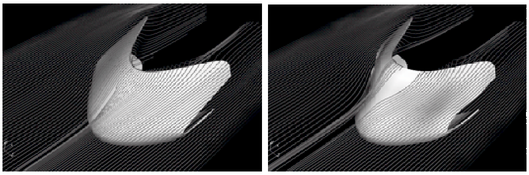

Figure 2. Fluid-dynamics analysis results performed on the initial geometry and on the modified geometry of a windscreen.

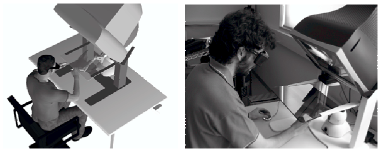

Figure 3. Use of haptic module based on the SenseGraphics system for the modification of the model of the windscreen.

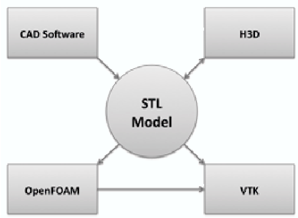

Figure 4. Data exchange among the PUODARSI modules.

shown through the active stereoscopic window of the SenseGraphics system. Figure 3 shows a designer that is modifying the shape of a windscreen model using the haptic module. The user is looking at a stereoscopic view of the model and is interacting haptically with it by using the stylus of the Phantom haptic device.

4.3. 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"). The common data format used for exchanging the geometric representation of the object among the various modules is STL, which is appropriately converted within each module (Figure 4). The data exchange through the network will not involve very large amounts of data, because, in order to perform real-time simulations, the data volume will never be too large.

4.4. Use of the System

Two users operate with the PUODARSI system: designers use the haptic module and analysts use the CFD module. The two users use the system in a collaborative way (Figure 5). The users can work in the same environment or can be geographically dislocated. At the moment the resulting data are visualized in a 3D environment. The next release of the system will allow the user to see the CFD analysis data displayed on top of the physical prototype of the object in an augmented reality environment.

5. DISCUSSION AND 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 products. The system supports two different setups: one is for the designer that uses the SenseGraphics workbench for performing modifications on the object geometry, and the other one is for the analyst that runs CFD analyses and visualizes the results in a 3D visualization environment. In a future release of the system the users will be able to add notes to the geometry and to the analysis results through an annotation module;

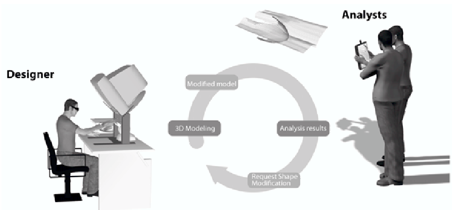

Figure 5. PUODARSI collaborative environment.

in addition the system will support and augmented reality visualization modality allowing users to visualize velocity vector of the flow on top of the physical prototype of the object analysed. The same object will be rendered in two different windows while the annotation will be related to the model and shared by users. The annotation module is under development, and is based on the VTK library for managing notes; it will be necessary to create two or more visualization windows for the same environment, or create a communication protocol between the two applications that share the same models.

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