Using Augmented Reality and interactive simulations to realize hybrid prototypes

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Abstract. Engineers and designers of various product development fields show an increasing interest in rapid prototyping as these help them to optimize their products faster and more precise. In this work we present an Augmented Realty (AR) application with a model size water turbine in order to demonstrate how rapid prototyping with a hybrid prototype, simulation data of water flow characteristics and an optical AR tool can be realized. The application integrates interactive simulation, a tangible user interface and several interaction concepts for 3D CFD. Due to the intuitive and automated workflow as well as seamless process iterations, the application is easy to use by users without expert knowledge in the field of parallel simulations. Our approach points out the main benefit and problems of AR in rapid prototyping and thus is an example for further application fields.

1 Introduction

Engineers in different development fields nowadays face real challenges: the complexity of products and quality standards increase while expenditure of time and money are required to decrease at the same time. In order to meet these challenges, various *rapid prototyping* techniques have been developed. For modelling the physical prototype, methods like stereolithography, selective laser sintering or 3D printing are used [1]. Thus, it is possible to modify characteristics like size, shape and surface of the object shortly. Recently, virtual prototypes have become a popular and commonly used technique in product development and optimization. They inclose a graphical computer representation of the geometry as well as characteristics of the object. This allows us to run computations and simulations on virtual objects while the engineer can modify the virtual model and adjust the parameters as needed. In this way, the virtual design and possible construction errors can be corrected before the physical prototype is build. By superimposing the physical and virtual prototype, modifications of components can be directly compared and evaluated in an easy manner. So far, the combination of physical and virtual prototyping has been integrated in the product development process only to a minor extend. Yet, the engineers' interest in these hybrid prototypes grows and some are already used in operative processes in the industry.

Virtual Reality (VR) techniques are today employed in early phases of the development process to evaluate the draft of the future product. Engineers benefit from VR techniques as they allow them to visualize the geometry of the object as well as the huge amount of simulation data in a demonstrative and intuitive way. Thus, managers and specialists from other faculties who are not familiar with the technical details are also able to interpret and use VR techniques. Nevertheless, not all aspects though can be captured and visualized sufficiently: Properties like shape, distance, optical appearance and haptics of materials, for example, can only be perceived on physical objects properly. In contrast, *Augmented Reality* (AR) techniques provide essential advantages by overlaying virtual content over the physical prototype. One of the major benefits of AR applications is the simultaneous judgment of multiple parameters. This comes into consideration when, for example, the object underlies strong deformations or material wear out. Here, AR techniques can help to measure the deviation from the original state. Another major benefit is the interactivity provided by tangible interfaces and interactive simulation. This is particularly relevant when the objects change their position or have movable components. The user can then modify parameters like shape, position and orientation of the object or components on the spot and see the simulation results according to the new modulation at once.

The overall aim is to develop AR applications that do not require special expert know-how but are easy and effective in use. In order to meet these requirements, several main process iterations have to be completed: grid generation, domain decomposition, simulations and calculations, post-processing for AR visualization and the setup of a tangible user interface. The quality of AR applications strongly depends on the performance of these interations.

A current important development area is the optimization of water power plants for electric power generation. Due to the field of operation, the water power plants require very complex techniques and have to be individually designed. In order to increase the efficiency of hydraulic turbines, several approaches are researched today. One important aspect is the investigation of the optimal design of the turbine runner, and the optimal blade angles for different operating points. In this work, an AR application with a model size Kaplan turbine is presented to demonstrate how rapid prototyping with a hybrid prototype and interactive simulation can be realized.

2 Related Work

In 1994, Milgram et al. gave a definition of a continuum of real-to-virtual environments to which two main parts they refer to as Mixed Reality (MR). The part where virtual elements are added to the real content is defined as Augmented Reality (AR), the other part where the virtual environment is complemented with real objects is called Augmented Virtuality (AV) [2]. Verlinden et al. [3] improve on the classification of AR systems given by Milgram et al. 1994 [4].

They categorize applications such as the one presented here as ”Video-Mixing AR”.

In his survey of 1997, Ronald T. Azuma describes AR as a variation of virtual environments and points out its supplementary function in various application fields like medical visualization, maintenance and repair, annotation, robot path planning and entertainment [5]. While some AR approaches aim at generating virtual objects that realistic that they can hardly be distinguished from the real environment, the focus in product development processes today is rather put on the ease of use of AR systems. Azuma mentions various basic challenges that have to be fulfilled in order to obtain a satisfying augmentation. Since then lots of research concerning optics and resolution, accuracy, registration of real and virtual objects, environmental and lighting conditions as well as marker tracking has been done. In his survey of 2001, Azuma denotes rapid technological advancements during the last years. This includes issues like tracking approaches, calibration, latency, displays and visualization problems [6].

Augmented reality techniques have been used in production e.g. for visualization of air flow in car and airplane cabins using CFD simulations [7]. Most AR applications make use of precomputed simulation data for visualization, although there has been some work by Schmalsteig et al. to couple AR and online simulations in the Studierstube project [8].

Various visualization environments have been used for computational simulation steering. Unitah/SCIRun [9], AVS [10], CUMULVS [11] and COVISE [12] provide integration of interactive visualization into the simulation workflow. COVISE has also been used to integrate tangible interfaces [13] to make parallel simulation on remote supercomputer resources accessible not only to the simulation expert but also to other engineers involved in product design.

3 An application: Design of a Kaplan turbine

Water power plants in flowing waters usually underlie extremely high variations of flow and head which often lead to pressure drop and finally to cavitation. Kaplan turbines are special water turbines that have adjustable rotor blades and thus can be operated efficiently even when flow conditions vary. When optimizing these hydraulic turbines, characteristics of the water flow like pressure and velocity distribution have to be investigated [14].

In this work we present an AR application based on interactive simulation in real-time and a tangible user interface. As a concrete example object we use a model size Kaplan turbine of 27 cm in height. The propeller shaped runner has four adjustable rotor blades that are turnable around their anchorage. The tangible user interface is realized with the optical marker tracking system ARToolKit [15]. Two pattern markers are used: the first marker of a size of 48mm was attached to the model turbine in the upper part in order to determine the position and orientation of the model. The second marker of a size of 27mm is fixed at the edge of a turbine blade in order to determine the rotation angle of the blade. In our setup, the pattern markers were viewed from a distance of about 50cm. The video camera we used was a HD camera with a resolution of 1400x1050 pixels.

4 Rapid Prototyping and Interactive Simulations

Prototypes are used in most phases of product development, to validate characteristic properties of the product or several of its parts. Since the development of physical prototypes is time consuming and expensive, virtual prototypes are used to replace them, particularly in earlier phases of development. This allows for faster changes in the initial product design, and therefor an improved development cycle.

To be able to evaluate the properties of a virtual prototype, its behavior has to be simulated numerically. In turbine design, *computational fluid dynamics* (CFD) simulations are used to optimize the machine for different operating points. The workflow of a simulation cycle consists of geometry generation, grid generation, domain decomposition, post-processing and simulation. We will outline this workflow in the following sections.

We have integrated the workflow into the dataflow-oriented *Collaborative Visualization and Simulation Environment* (COVISE), allowing for presentation of the simulation results in immersive or augmented reality environments, and collaborative product development through the use of hybrid prototypes.

4.1 Hybrid Prototypes

Both physical and virtual prototypes are not always able to represent the finished product satisfactory. Physical prototypes can diverge from the behaviour of the finished product because of e.g. different processes used in the development, different materials or the high amount of manual development involved. Some parameters can only be determined numerically, because a physical experiment would be too time consuming, expensive or dangerous. Virtual prototypes too are not able to exactly represent reality. The design and simulation is based on simplified physical models, geometry often has to be approximated by polygonal meshes, and properties of certain materials may not even be known.

To overcome these limitations, hybrid prototypes aim at combining the use of physical and virtual prototypes. They enable the engineer to compare simulation and experimental results, and to optimize the design of the virtual and physical prototypes by evaluating the results of both processes corporately. Hybrid prototypes integrate geometry and behaviour in a computer representation while allowing a user to interact with a physical model and possibly evaluate the behaviour of the prototype in a test environment.

Physical representation of objects and physical feedback with computer generated information is combined to better analyze the behaviour or properties of the product.

4.2 Grid Generation

The computational mesh for the numerical flow simulation of the turbine runner is an unstructured grid based on hexahedral elements. The grid is generated automatically by a custom COVISE module "AxialRunner". This module allows for parametrized design of axial flow turbine runners. Additionally to the computational grid, the module generates boundary conditions used in the CFD simulation, and polygons representing the surface of the shrouds and the hub of the turbine runner. This virtual object can then be used for realistic occlusion effects of the turbine model with respect to the post-processed simulation results, and for simultaneous visualization of the simulation results in immersive environments. FENFLOSS, the CFD simulation used in this project, has been extended to be able to read unstructured grids in COVISE format.

The size of the computational grid can range from approximately 100.000 elements for interactive response times to millions of elements for a more accurate, however more time consuming calculation, depending on the computing resources available.

4.3 Domain Decomposition

The computational grid is split into several parts for parallel processing of the simulation on remote computing resources. Generally, the number of partitions of the mesh should be the same as the number of compute units (e.g. CPU cores) available. Because communication between different processes used in the simulation is expensive, even on high-bandwidth and low-latency networks such as InfiniBand, the computational grid must not be subdivided into too many partitions.

We implemented a COVISE module using METIS [16] as a library for the partitioning of the mesh. METIS provides a fast and stable solution for domain decomposition. Besides, it is simple and practicable to use. In Fig. 1, you see a dataset split into four domains with interface elements (yellow cells) between these domains. Because of the high overhead of communication between the cluster nodes during the simulation, there is no advantage in subdividing the relatively small computational grid used in this interactive simulation into more than four partitions. For larger simulations that don't require interactive steering, the domain decomposition module is parametrizable to split the computational grid into domains suitable for the available resources.

4.4 Simulation

FENFLOSS [17] is developed at the Institute of Fluid Mechanics and Hydraulic Machinery (IHS) at the University Stuttgart.

FENFLOSS can be used for the simulation of incompressible flows and uses Reynolds-averaged Navier-Stokes-equations on unstructured grids. The simulation code can be applied to laminar and turbulent flows. The turbulence models

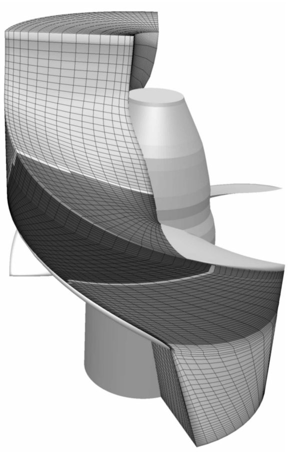

Fig. 1. Decomposition of the computational mesh into four parts

used are turbulent mixing length models as well as various k-ϵ models, containing nonlinear k-ϵ models and algebraic Reynolds stress models.

The solver works for 2D or 3D geometries, which can be fixed or rotating and either steady state or unsteady problems. FENFLOSS can also handle moving grids (rotor-stator-interactions) and contains methods to calculate free surfaces flows. It can be used on massively parallel computer platforms and is optimized for vector processors e. g. NEC SX-8. The program employs a segregated solution algorithm using a pressure correction. The parallelization takes place in the solver, which uses BiCGStab2 including ILU pre-conditioning. Coupling of fixed and moving grids is accomplished by using integrated dynamic boundary conditions.

FENFLOSS provides a user subroutine API, which can be used to call user supplied functions at different places in the solver. We used the subroutine API to handle data transfer between the simulation and the visualization environment COVISE. After each time step, the computed pressure and velocity fields are sent to COVISE, where the data can be further post-processed and visualized. The coupling of the simulation and the visualization environment is implemented by using a socket connection between the solver API and a custom COVISE simulation module. The COVISE module implements the "coSimLib" interface, which was designed to provide an abstraction layer for simulation coupling. The simulation module integrates transparently into the COVISE workflow by providing the computed values, scalar and vector data, in a format accessible for further post-processing in COVISE data format.

Parts of the simulation results, e.g. the pressure and velocity values at the outlet of the turbine runner, can also be used as boundary condition for other, possibly coupled, simulations. The computation of the flow in the wicket gate and the draft tube where not part of this simulation.

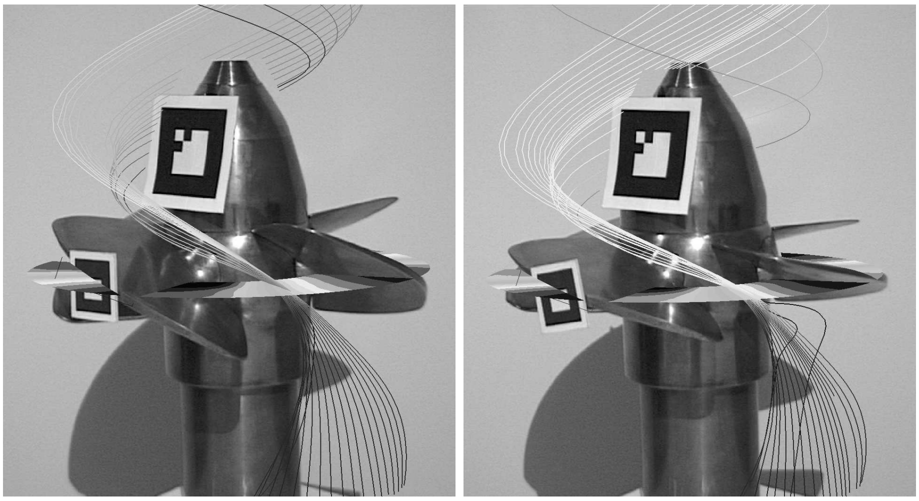

Fig. 2. Post-processed simulation results in an augmented reality environment. The angle of the blades used for the two simulations differ by 6 degrees.

4.5 Augmented Reality and Computational Steering

In our exposition, a high resolution *Head Mounted Display* (HMD) is used to explore the physical model of the kaplan turbine. The camera pictures of the HMD are captured and analyzed by a modified version of ARToolKit [15]. ARToolKit analyzes the picture at around 10 frames per second on a Pentium M 1.6. It returns the position and orientation in six degrees of freedom of all markers which are completely visible. By using the position and orientation of the object marker, the post-processed simulation data can be properly overlaid with the picture taken by the cameras. By simply rendering the virtual model of the kaplan turbine generated by the "AxialRunner" module to the z-buffer, we achieve realistic occlusion of the physical model and the post-processed simulation data.

The second marker, which is attached to one of the turbine blades, is used to obtain the angle of the turbine blades from the tangible interface. This angle serves as an input parameter for the "AxialRunner" grid generation module. By changing an input parameter, e.g. the angle on the physical model, the engineer is enabled to influence a parallel flow simulation of the turbine runner, and explore the resulting data. When an updated computational mesh is generated by the grid generator, the CFD simulation is restarted. Because the grid does not differ too much between simulations, and the number of nodes as well as their connectivity stays the same, the computed results of the previous iteration can be uses as a starting point for newly setup simulation. This allows for faster convergence of the numerical simulation and therefor improved perception of interactivity by the user.

The other modules used in the workflow are standard COVISE modules used for data analysis and visualization, e.g. Tracer, Cutting Surface and Colormap modules. A visualization of the resulting post-processed data, combined with the physical prototype of the turbine runner as can be seen by using a HMD, are presented in Figure 2.

With COVISE, collaborative visualization and exploration of the results in multiple different, even spatially distributed, environments. By using tangible interfaces, a more natural mode of operation is possible compared to a traditional user interface which e.g. makes typing in coordinates necessary to move objects. The natural perception of the model in comparison to a simple monitor image is another important advantage.

5 Discussion

Superimposition of real and virtual objects provide useful information for a variety of purposes. Hybrid prototypes can be used to evaluate simulation data with respect to measurements. In turbine design, verifying the simulation of stationary parts, such as the wicket gate and the draft tube, can easily be done in a test facility. To verify moving parts such as the turbine runner, the test facility has to be equipped with a stroboscope, which can be used to make the runner appear stationary for a given constant rotational speed.

Physical prototypes are also quite often used for teaching purposes. We believe that the comprehension of complex systems can be strongly improved by using hybrid prototypes including coupled online simulations.

For production usage in rapid prototyping, augmented reality applications often are too inaccurate and require a lot of time to setup for each changing dataset. Camera tracking by using ARToolKit and pattern markers works quite well for tracking of the prototype. Although, it is not precise enough for input parameters where small changes lead to huge computational expenses, such as the blade angle in the application outlined above. This shows the need to provide additional sensors for user input. When a hybrid prototype is to be used in collaborative sessions, there has to be a way to provide feedback to the tangible interface. If a parameter is changed using the virtual representation of the object, the respective parameter in the tangible interface should be changed also. These parts of the tangible interface would have to be developed specifically for each application leading to an increased development time.

6 Conclusion

In this work we have presented an AR application with interactive simulation and a tangible user interface in order to demonstrate how rapid prototyping can be supported by hybrid prototypes. Today, even challenging simulation tasks like 3D CFD can be solved in proper time and with reasonable effort. Our approach with a model size water turbine shows that the superimposition of virtual simulation data with a real prototype helps to understand and interpret complex relationships. A set of user interfaces for the modification of input parameters, the preparation of visualization modules and the orientation detection of movable components allow us to control the application. With these user-friendly interfaces and seamless automated workflows even engineers and designers without expert knowledge in simulation are able to optimize solutions. The automated process chain of interactive simulation includes grid generation, domain decomposition, the simulation of incompressible flows, a tangible user interface as well as post-processing and visualization.

We have identified various challenges that have to be met. Although the tracking of objects using ARToolKit is good enough for superimposing data with the physical prototype, it is not exact enough for input parameters in online simulations. This increases development time, because the easy to setup method of getting input parameters via additional markers has to be replaced with application-specific sensors that provide accurate values.

In the future, we would like to integrate other parts of the turbine design into our workflow. This includes the wicket gate and the draft tube, as well as a coupled online simulation that allows for interaction and back coupling of the different parts. Additional sensors for collecting the angle of the shrouds in the wicket gate and the turbine blades in the runner could be integrated into the tangible interfaces.

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