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An interdisciplinary approach to validate mechatronic systems in early product development stages

Maik Auricht
Technische Universität Berlin
maik.auricht@tu-berlin.de

Boris Beckmann-Dobrev
Technische Universität Berlin
bdobrev@mail.tu-berlin.de

Rainer Stark
Fraunhofer IPK Berlin
rainer.stark@ipk.fhg.de

Abstract

A fast and efficient solution for the evaluation of mechatronic systems in early development stages provides Smart Hybrid Prototyping (SHP). It represents an intermediate stage between the digital and the physical prototype. In particular, it allows multimodal experiencing of mechatronic systems, the human is better involved in evaluating the overall system. To demonstrate the concept of the Smart Hybrid Prototyping approach and to evaluate the technological feasibility an example from the automotive industry was chosen: the development of car tailgates.

Keywords: Smart Hybrid Prototyping, Virtual Reality, Mechatronics

Introduction

Within the last 10 years, product development processes have changed significantly. The time-to-market has been decreased [1], the number of functionalities of a product has been raised, the portfolio of companies has been changed in terms of more variants [2] and with that, the complexity of the development has been increased [3]. In the end, the product has to satisfy customer demands. There are several validation cycles within the development process to make sure, the right product is being developed in terms of intended purposes of the customer. Beyond that, there are also verification cycles to make sure the requirements of the customer are fulfilled.

Virtual Reality tools for engineering tasks like the Visual Decision Platform (VDP) of ICIDO, VRED of PI-VR, DeltaGen of RTT AG or VirTools of Dassault Systèmes provide functionalities to analyze product properties. DMU-analysis functions like positioning, cut plane or measuring are as well available as variant comparison, ergonomics and assembly analysis functions. Advanced solutions provide real-time simulation of flexible parts or photorealistic visualization, but these features are still in the state of research.

The combination of digital prototypes with physical elements to realize real-time force feedback interaction is relatively new. There are different approaches within this field. Bordegoni et.al., for example, describe a framework for applications using mixed prototyping and Mixed Reality techniques. Therefore the Virtual Reality environment is enriched with physical elements (switches, buttons or other mock-ups). Hereby it is possible to evaluate for instance the ease of use, sensorial feedback or accessibility [4]. But still, despite the different existing approaches, it is important to combine the areas of Virtual Reality (using existing development data) and haptics. The multimodal experience of systems is an important step in order to get the same feeling of the product or the functionality the costumer is going to get. It is necessary to use State-of-the-Art technologies, so that the user experiences the real product. The following chapters will present a new approach addressing the aforementioned aspects: Smart Hybrid Prototyping.

Definition of Smart Hybrid Prototyping

The digital test models, called CAE models and thus enriched Digital Mock-Ups (DMU), arose from the need to replace physical experimental models, so-called Physical Mock-Ups (PMU) by calculation and simulation. Today DMUs are used for geometric integration, collision analysis, assembly and disassembly simulation, packaging and ergonomics analysis [5]. In order to validate mechatronic products in the early development stages, an extension of DMU to functional aspects towards a Functional DMU (FDMU) and the support of multi-disciplinary collaboration of the domains of mechanics, electronics and software-development is essential [6, 7]. Smart Hybrid Prototyping (SHP) is an innovative approach for product development being part of the overall product creation process beginning from product idea up to the release of mechanical and mechatronic systems. The Links available the digital domain specific models of mechanics, electronics, and software. It enables an interactive experience of the product behavior with a digital product representation and laboratory equipment under the restrictions of correctness, functional comparativeness and cost-efficiency. Furthermore it allows an interactive evaluation of product functionalities and product behavior for designers as well as customers in real-time. The Smart Hybrid Prototyping technology is to be understood as a continuum between CAE, DMU / PMU and FDMU. Therefore the developed system serves as a bridge between physical reality and digital virtuality and allows the experience of product characteristics which cannot be visualized, such as weight, inertia and damping. In addition, validations can be composed modularly and independently at different levels of maturity of mechanics, electronics and software or as a total system.

Many tools use human models for the ergonomic verification of digital products. This kind of indirect interaction is not suitable to experience the functional behaviour of the product. Ideally the user is enabled to interact directly with the digital prototype. A kind of direct interaction can be realised by using input devices like the CybeGlove. Data gloves are pure input devices without haptic feedback. Mechatronic solutions like the CyberGrasp or the CyberForce system extend data gloves to wholesome haptic interaction devices [8]. Figure 1 shows for example the Haptic Workstation from Cyberglove Systems. Such devices support many degrees of freedom with the goal to be universally applicable. Unfortunately, this leads to high complexity and the devices are very expensive. At the same time universal haptic devices are still limited regarding working space and force feedback. For the purpose of Smart Hybrid Prototyping affordable solutions are required.

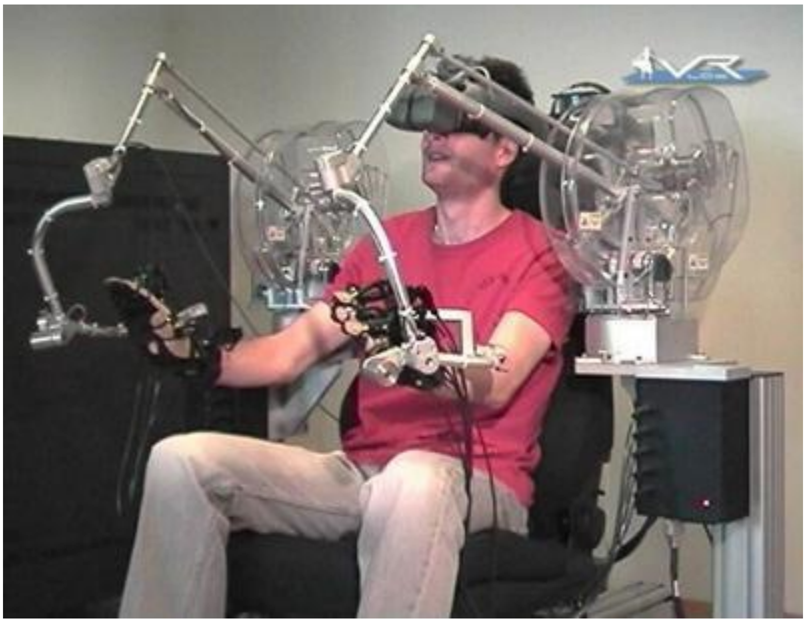

Figure 1 Haptic Workstation of Cyberglove Systems [8]

Proof of Concept

To demonstrate the concept of the Smart Hybrid Prototyping approach, an example application from the automotive industry was chosen: The development of a car tailgate. In the design phase, many ergonomic features of a car tailgate are largely determined. At this stage, only indirect ergonomic studies with the help of digital human models can be carried out. The SHP approach uses the "state-of-the-art" DMU. Direct functional or ergonomic studies are only possible by the costly construction of a Physical Mock-Up (PMU). It is desirable that system alternatives of the tailgate such as relocating of anchor points of the gas spring, using different hinges or additional masses for system extensions can be directly experienced on the digital model for engineers and decision makers. Since the variability of physical prototypes is limited, continuous adjustments on the CAD / CAE model are only transferable with great effort to the PMU. With the help of the SHP approach, the effort can be minimized and developers get an immediate feedback. Therefore the DMU is extended with a CAE simulation intelligence being able to demonstrate trajectory and forces. Haptic interaction devices transform the forces into a kinesthetic simulation [9]. To evaluate the developed hybrid prototype, a Ford Fiesta of the current seventh generation was chosen. The behavior of the hybrid prototype could be compared to the real system by measurements on the physical prototype and with the help of test persons. The development of the hybrid tailgate prototype took place in three steps.

1. A DMU was built based on CAD / CAE models, kinematic and dynamic behavior were modeled and simulated.
2. For the true kinesthetic output of the simulation results, a haptic interaction device, called feedback device, was designed and built.
3. Finally, the simulation results and the feedback device were integrated in a Virtual Reality (VR) environment.

For the simulation of the tailgate, the CAD-/CAE-/CAM-System NX 6 from Siemens PLM was used. The kinematic behavior of the tailgate was modeled. Hereby a simplified CAD / CAE based DMU model. In addition to the modeling of the tailgate kinematics the major challenge was to map the dynamic properties of the gas spring. The spring was defined as a standard component and installed in the real prototype. Since the gas spring is composed of a spring and a damper, the spring-damper properties were measured separately and were implemented in the intelligent DMU model. The acquisition of the spring-damper properties were measured separately, as the manufacturer's data sheet did not contain all the required characteristics. The acquisition of characteristics of a foreign product is a non-trivial task. According to the manufacturer's data sheet, it should be measured in the installed state. Since the hybrid prototype should be compared with the real system in order to evaluate the methodology, the anchor points of the real gas pressure spring were also measured and transferred into the digital model. Figure 2 shows the comparison of the simulation in NX and the measurement of the real prototype.

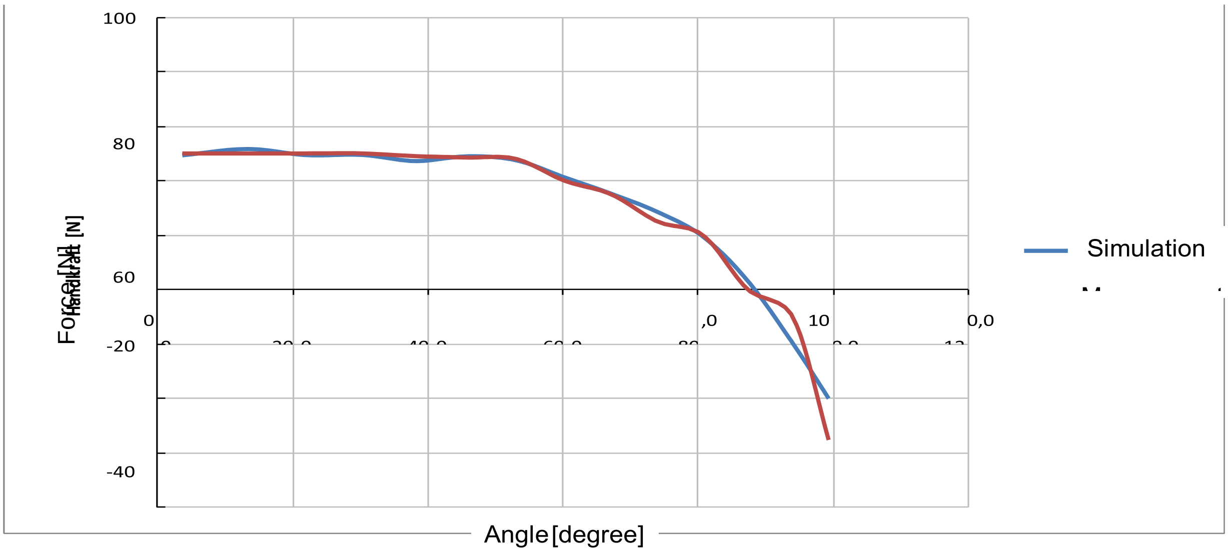

Figure 2 Comparison of the simulation and measurement results

There is still the ability to set different anchor points and/or gas spring characteristics and to simulate it. This was tested within the evaluation of the Smart Hybrid Prototyping approach being the major motivation for the development of the hybrid prototype. After the virtual tailgate was modeled kinematically and dynamically, an automated series of simulations of opening and closing cycles with different forces and speeds were carried out. Within NX, motion simulations are not calculated in real-time, therefore the discretized simulation results were exported to spreadsheets and transferred to the real-time environment of the haptic device. After the first simulation, further simulations were made with different anchor points and different spring characteristics. Hereby it was determined that 15 minutes were needed to change the simulation model, to execute the simulation and to export the simulation results in new tables. Thus, the evaluation of different gas springs for several anchor points is theoretically possible within a day. The feedback device was designed based on the experience of earlier developed interaction devices. For example, the GRASPit system, developed at the Fraunhofer IPK, has two force-feedback interaction devices of the type PHANToM 3.0 from SensAble. Both interaction devices support three translational degrees of freedom both input and output. By combining the two interaction devices with an end- effector, a new system was created that allows up to six degrees of freedom (3 translational, 3 rotational) [9]. Although the system GRASPit combines two of the largest haptic interaction devices to one device, it could neither achieve the required forces and moments nor cover the working range of the simulated car tailgate. In addition, the GRASPit system was designed with six degrees of freedom for versatile installation and removal studies in the classical sense of the DMUs. In the case of a tailgate simulation, however, only a rotational degree of freedom is required. Despite a blocking of not used degrees of freedom, the required rigidity could not be achieved. Furthermore, the system is not compatible with the philosophy of

Smart Hybrid Prototyping, due to the very high prices for high-end haptic interaction devices. Based on the above findings it was decided to develop a new feedback device that meets the requirements of the tailgate simulation adequately, while providing a much cheaper solution than the GRASPit system. Nevertheless, the used components are high quality industrial solutions.

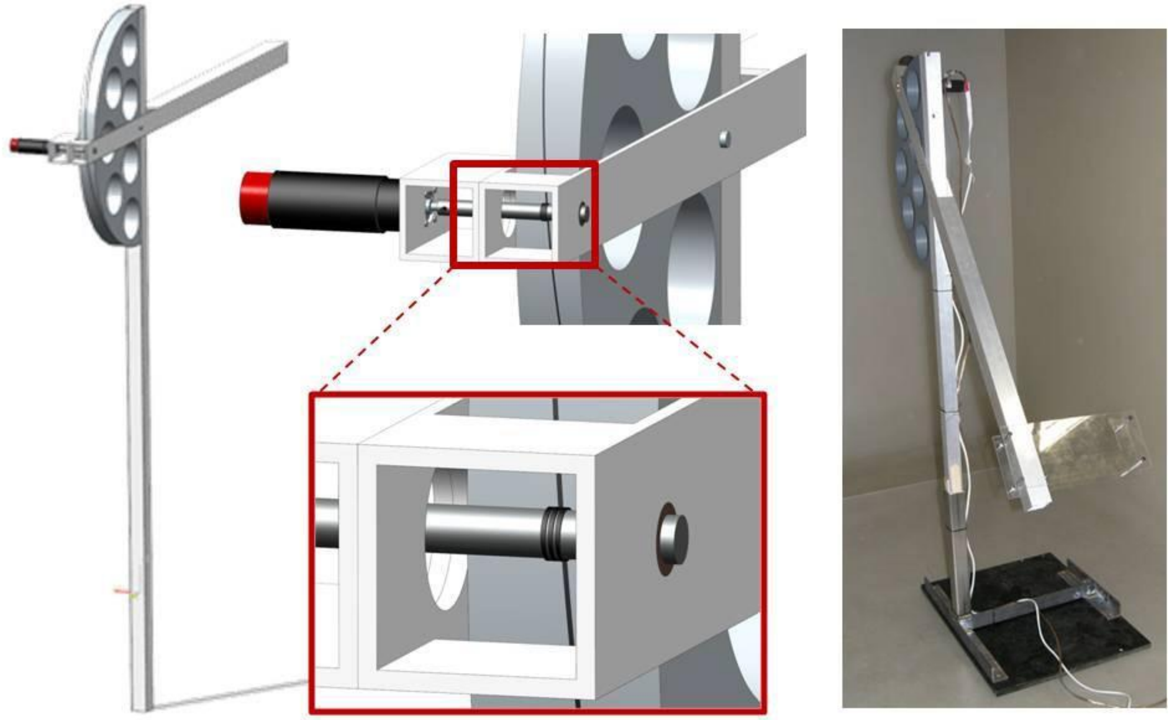

Figure 3 The haptic device as a digital and physical prototype

The feedback device (Figure 3) consists of a brushless Maxon DC motor from the type RE35 with an integrated optical incremental encoder and a metal-ceramic planetary gear. The gear reduction of the motor and encoder is 4.8. Thus, a torque of up to 1.1 Nm is available. The encoder provides 1000 increments per cycle rotation. The motor is powered by a Maxon PWM servo amplifier and is supplied with the necessary flows (up to 5 amps). Since the motor acts as an electro-mechanical brake, by the PWM voltage and the high power performance of the servo amplifier the optimal efficiency of the engine is achieved. Motor and encoder are read out and controlled by industrial controller from the company Addi-Data. For that reason a Linux driver was developed, including the basic functionalities. The interactive simulation was implemented in C++. The simulation uses the driver to calibrate the encoder, to read out the data and to control the motor. For the mechanical realization of the feedback device, a lever arm was used. By using a steel cable, the motor was clamped in backlash-free to realize a gear reduction of more than 50x. The usage of a planetary gear (4.8x reduction) results in an overall reduction of 250x. A lower reduction could have been used if a smaller motor would have been applied. But as the motor is attached to the end of the feedback-device, a bigger motor would impair the dynamic behavior of the device. The simulated dynamic system behavior was determined by NX simulation results. Depending on direction and velocity of the feedback-device the correspondent spring-damper values are read out of the simulation tables and interpolated if necessary. The immersion is intensified by enabling users to experience the mechanical behavior both haptically and visually in a Virtual Reality environment. Acoustics were not considered, but the gas spring is a standard part and already available in an early phase of product creation. Therefore recording of its acoustic behavior depending on direction and velocity is possible at any time.

The methodology that is used to merge simulation, visualization and interaction into one application is known as Model-View-Controller (MVC). This methodology was implemented in a compelling way. The strict division into model, view and controller allows a modular set-up of the tailgate-simulation. That means that the application can be upgraded with new components and can be reused for new applications. As a visualizing-system the RENDERit system was used, that was developed at the Fraunhofer IPK for immersive Virtual Reality (VR) facilities [10]. RENDERit is operated in a cluster and is considered as a distributed system. The interactive simulation and the feedback-device are developed and operated on a separate computer. For the network-side implementation of RENDERit, the also own developed TUI-Framework was used. The SHP solution was placed in a 5-sided VR-Cube (also called CAVE) at the Fraunhofer IPK in Berlin (Figure 4).

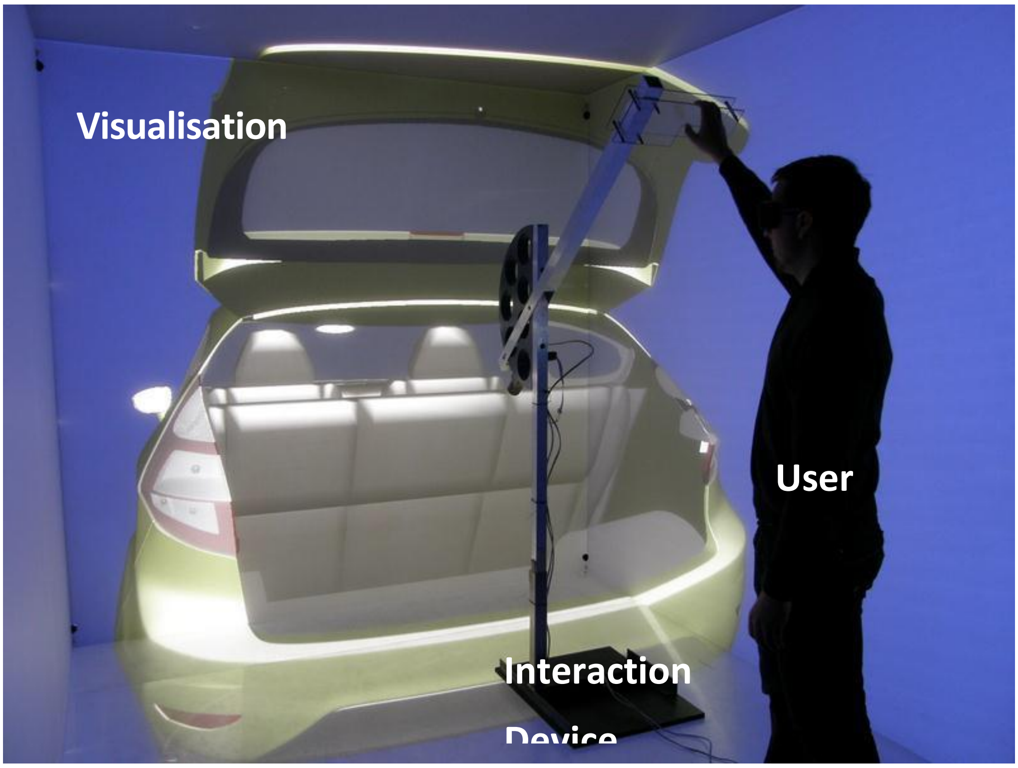

Figure 4 The complete solution of the SHP within the CAVE at the Fraunhofer IPK

A 2-sided Holobench that was also available could not display the virtual model in actual size. So called Powerwalls provide a cost-effective alternative for the rendering of the tailgate simulation in actual size. This possibility of immersive rendering should be sufficient for most industry-users of Smart Hybrid Prototyping. Additionally a linking of the interactive simulation to the Visual Decision Platform (VDP) from ICIDO is planned, because this visualization system is widely used in automotive industry.

Benefits

Today's engineering analysis practice to provide simulation based parameter plots for customer oriented product function behaviour is not sufficient to correctly assess the final customer perceived function performance. Formerly used final product function verification with full physical prototypes in many cases is no longer affordable due to high cost, longer lead time for the construction of physical prototypes and significant build efforts. Therefore, it becomes indispensable that product functions which affect direct user/customer product interaction need new ways of "digital model interaction prove out". The haptic interaction behavior has been recognized as a key interface in the human-machine interaction to correctly assess the functional behaviour of mechanical or mechatronic systems such as doors, levers, electronic switches and knobs, window regulars etc. Therefore the goal is to provide intelligent "Smart Hybrid Prototyping" solutions to directly test the "human being interaction in the loop" as real time interplay with the digital model of the future product via force-feedback interactions.

Outlook

In 2011 Siemens PLM introduced with NX 7.5.3 the Mechatronics Concept Designer (MCD), an innovative Systems Engineering approach for parallel development of mechanical and electrical/electronic components. MCD supports the multidisciplinary product development and the decision making during the conceptual phase where different designs can be evaluated and optimized at an early stage. It allows creating of a functional structure of the machine components and provides a common language for mechanics, electronics and software development. The benefits are a real-time simulation of machines with physical behaviours like collisions and friction as well as event-driven objects such as sensors and actors. An on the fly interaction with the digital machine model allows a fast evaluation of different designs.

With the V6 engineering platform, Dassault Systèmes introduced another innovative Systems Engineering approach called Requirements, Functional, Logical and Physical Design (RFLP). Major benefit of the RFLP approach is the traceability of requirements through the different stages of the product development process. To allow traceability, RFLP splits the development process in four stages and allows for the definition of links between them. In the first stage the requirements will be determined. The second stage describes the functional behaviour of the product in a state graph similar way. The third logical stage introduces an innovative modeling with the usage of the Open Modelica language. In the last stage the classical CAD modeling takes place. Links between those four stages provide a qualitative and quantitative traceability of requirements and allow interdisciplinary co-simulations where mechanical, electronic and logic components affect each other.

Smart Hybrid Prototyping enters new approaches like RFLP and MCD to realize functional solutions for human beings in the loop into the overall solution space of Model-in-the-Loop (MiL), Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL) in the early Functional Digital confirmation mock-up framework.

To ensure not only validations on tailgates but also on doors, a new system is currently being developed. This new device is equipped with a rotational hinge in order to allow both door and tailgate validations. An electrical lifting column allows different tailgate or door heights. The new system is planned to be a Plug-and-Play solution. The main focus is the usability and acceptance of this new way of validating mechatronic systems. The aim is to build a ready-to-use product which can be plugged-in in nearly every computer used for simulation.

Literature

[1] Kahn, K. B.: *The PDMA Handbook of New Product Development,* Second Edition 2004.

[2] Schuh, G.; Schwenk, U.: *Produktkomplexität managen.*, München 2001.

[3] Lindemann, U.; Maurer, M.; Braun, T.: *Structural complexity management,* An approach for the field of product design, Berlin 2009.

[4] Bordegoni, M.; Cugini, U.; Caruso, G.; Polistina, S.: *Mixed prototyping for product assessment: a reference framework:* Int J Interact Des Manuf 2009.

[5] Freund, G.: *Entwicklung eines methodischen Vorgehens zur Einführung von Digital Mock-Up-Techniken in den Produktentwicklungsprozess der Automobilindustrie,* Dissertation an der Fakultät für Maschinenbau, Verfahrens- und Energietechnik der Technischen Universität Bergakademie Freiberg 2004.

[6] Stork, A.: *FunctionalDMU: Co-Simulation mechatronischer Systeme in einem DMU-Umfeld, In:* ProduktDatenJournal (2010) 01, S. 44–48.

[7] Enge-Rosenblatt, O.; Clauß, C.; Schneider, A.; Schneider, P.: *Functional Digital Mock-up and the Functional Mock-up Interface – Two Complementary Approaches for a Comprehensive Investigation of Heterogeneous Systems,* Clauß, C.: 8th International Modelica Conference 2011.

[8] Cyberglove Systems: *Haptic Workstation,* URL: http://www.cyberglovesystems.com/sites/default/files/pg17_0.jpg.

[9] Krause, F. L.; Israel, J. H.; Neumann, J.; Beckmann-Dobrev, B.: *A 6-DOF user interface for grasping in VR-based computer aided styling and design:* VRST '05, Proceedings of the ACM symposium on Virtual reality software and technology 2005.

[10] Neumann, J.; Beckmann-Dobrev, B.; Kulf, L.; Israel, J. H.; Stark, R.: *Ein Renderingsystem für immersive Anwendungen in Forschung und Lehre, G*ausemeier, J.; Grafe, M.: Paderborner Workshop Augmented & Virtual Reality in der Produktentstehung, Paderborn 2009.