A HAPTIC BASED HYBRID MOCK-UP FOR MECHANICAL PRODUCTS SUPPORTING HUMAN-CENTERED DESIGN

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ABSTRACT
The overall goal of the design process is to create products of good usability. A human-centered design process is characterized by a continuous involvement of the prospective user of the product. This also comprises user-based concept assessments and design optimizations. For this purpose in many cases it is necessary that the user is given the possibility to perceive the product emotionally. Thus the flexibility of digital mock-ups well established in digital engineering can't be used. Instead, physical prototypes are often indispensible. In this paper a ***Hybrid Mock-Up*** approach is presented that allows a physical interaction with virtual prototypes. The behavior of the product is simulated digitally whereas elements of the human-machine interface are emulated using a generic haptic device. The benefit of the approach is that for the user a realistic product perception is achieved without having to dispense with the advantages digital engineering offers: saving of costs and time due to a reduction of physical prototypes. The approach is illustrated in a case study of a crank driven car jack.

Keywords: Hybrid Mock-Up, human-centered design, computer haptics, design space exploration

1 INTRODUCTION

The overall goal of the design process is to create products of good usability. Usability means the degree to which the product satisfies its intended purpose with reference to a particular group of users. Therefore all duties, objectives and characteristics of the prospective group of users must be taken into account. The human-centered design process according to EN ISO 9241-210 [1] depicted in *Figure 1* comprises four main phases: at the beginning the product's context of use is analyzed. This includes collecting information about the users of the product, the tasks they wish to solve and the technological boundary conditions that have to be kept. Based on this information design specifications are defined that serve as requirements for the subsequent concept phase. Afterwards the generated concepts are evaluated. In order to ensure that all user specific demands have been met, it is crucial to involve the users into this evaluation process. In general the users will judge a technical product not only on the basis of hard, nameable attributes but also on the basis of emotional impressions. In case of a hi-fi system for example it is regarded as a criterion of quality when knobs or sliders are moving with a certain amount of resistance. Except perhaps for the visual appearance it is hardly possible to predict such emotional impact solely by means of digital simulations. In many cases there is a need for the users to perceive the product so practical tests on physical prototypes are indispensible for a user-based evaluation of concepts. However, because product design is an iterative process the expense in time and cost, that the making of physical prototypes entails, has to be considered problematic.

In this paper a ***Hybrid Mock-Up*** approach for mechanical products is presented which can be regarded as a middle course between a digital mock-up and a physical prototype. The idea is to emulate elements of the product's human-machine interface (e.g. knobs, sliders, cranks) using generic haptic hardware whereas the physical behavior of the product is reproduced by a digital simulation. The benefit of this approach is that the user can interact with the virtual product in a direct and intuitive manner. This permits to carry out a user-based evaluation of design concepts avoiding the expense of physical prototypes. Moreover the underlying digital product model allows design changes to be carried out very quickly which leads to short iteration loops within the design process. It is possible to alter selected design parameters in real time whereby the user instantaneously recognizes the consequent effects on the product's behavior. Thus the approach also resembles a tool for design exploration.

After an overview on related work and the state of the art in computer haptics, the work methodology is presented in detail. It is shown how a generic haptic device can be used to emulate the behavior of mechanical components of the human-machine interface and which special simulation techniques have to be used to match the real time requirements of a haptic simulation. Finally the ***Hybrid Mock-Up*** approach is used in a case study to optimize the operational comfort of a crank driven car jack.

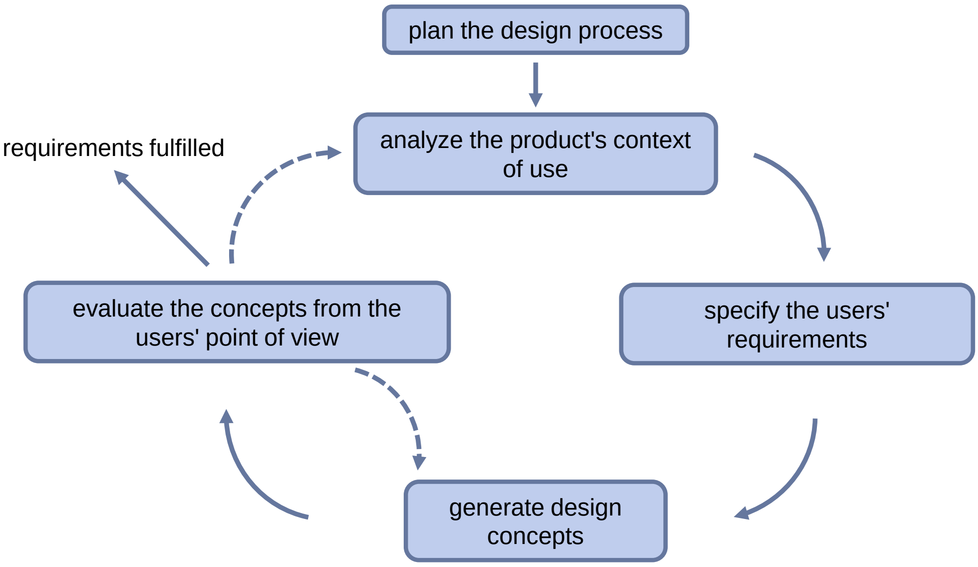

Figure 1. Human-centered design process according to EN ISO 9241-210

2 RELATED WORK

In this section a short overview on related work in human-centered design, computer haptics and ***Hybrid Mock-Up*** is given.

The origins of human-centered design lie in the field of software engineering. Computer systems can easily become very complicated, difficult to operate and prone for human error so that the need for a more human-tailored design was recognized quite early.

The standard EN ISO 9241-210 *Ergonomics of human-system interaction* [1] provides guidelines for the design of interactive computer-based systems. A prototypic human-centered software design process is introduced. Maguire [3] adopts this standard and suggests several concrete human-centered design methods to support each phase of the process. In particular he points out the importance of a user-based assessment to evaluate concepts generated during the concept phase.

Haptic devices were developed for artificially stimulating the human sense of touch. Usually the stimulation is achieved by applying forces to the human body which are generated by computer controlled actuators. The first haptic devices were used as components of telemanipulation systems in the nuclear and subsea industries. With further progress in computer technology and decreasing costs they could also penetrate into several other fields, like medicine, aerospace and defense [3]. In the last years haptic feedback systems have been introduced to support engineers in the design phase. Typical applications are maintenance and assembly simulations commonly carried out in combination with 3D virtual environments. Moreover Liu et al. [4] introduced a haptic-based CAD system which allows a pottery like modeling of freeform surfaces.

Hybrid Mock-Ups are simulation environments which combine computer-based digital simulations with physical components. Gausemeier et al. [5] used this approach for optimization tasks in vehicle ergonomics. A car with the roof removed was used to keep a test person in a natural driving position whereas certain elements of the car affecting the drivers field of view (e.g. A-pillar) were virtually superimposed into the environment using head mounted displays. Kimura et al. [6] used computer haptics and numerical simulations to mimic the touch and feel of mechanical switches taking into account disturbances caused by manufacturing discrepancies and wear. In a way their approach is similar to the objective of this paper but focuses on the user interface by itself whereas the present work aims at the behavioral real time simulation of the whole product including its visual appearance.

3 WORK METHODOLOGY

3.1 Overview

In order to enable the user to physically interact with a virtual prototype, elements of the human-machine interface are emulated using a generic haptic device. User input is read from the device and passed to a simulation system which reproduces the physical behavior of the product to be evaluated. Forces and torques are obtained from the simulation as a response to the user input. Via the haptic device they are applied to the user who hereby perceives the physical response of the product. Because the simulation system relies on a parametric product model it is possible to interactively alter the design of the product and carry out optimizations using the methodology of design exploration.

Computer haptics are time critical systems. Therefore all simulations involved in the ***Hybrid Mock-Up*** have to be capable of being carried out in real time. Unfortunately most numerical simulation techniques that are well established in digital engineering don't match this requirement. On up to date hardware a finite-element-analysis (FEA) problem of medium size for instance usually takes a couple of hours to be processed. A suitable solution for this problem is the following procedure: a pre-calculation of costly simulation tasks is performed. Based on the pre-calculated data parametric response surface models (RSM) are created that can be evaluated in real time on standard PC hardware. Consequently, the proposed approach comprises two main elements: an offline process of model preparation and an interactive real time simulation system.

3.2 Model Preparation

The process of model preparation as depicted in *Figure 2* starts with the creation of a parametric product model. Therefore a set of parameters (e.g. affecting geometry or material) has to be defined that marks out the design space to be explored. Most modern CAD systems offer parametric functionality which makes this task quite feasible. Moreover the possibilities for the user to interactively alter the state of the product have to be considered. These manifest themselves as additional parameters in the product model and shall be denoted as user input in the following. The product will react to the user input by changing several of its physical state variables, which shall be called system responses.

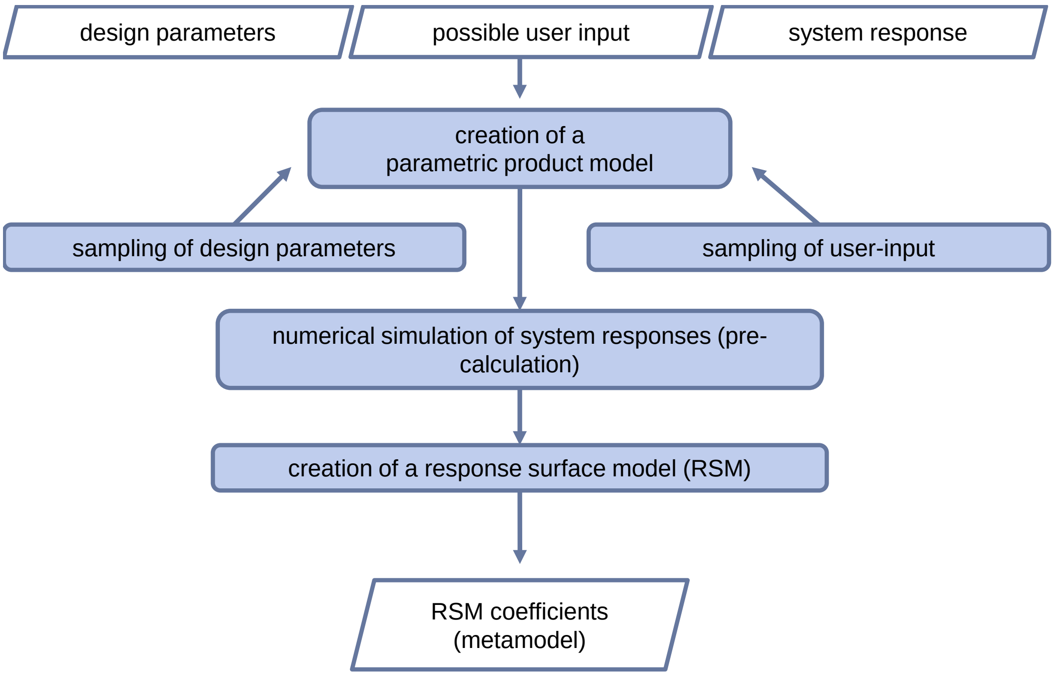

Figure 2. Process of model preparation

For the pre-calculation of the system responses the following procedure is carried out: A number of discrete samples are chosen from the range of every design parameter. Further the ranges of the parameters representing the user input are discretized into a sufficient number of samples. Then for

every combination of samples a numerical simulation is performed in order to determine one system response depending on the design parameters as well as on the user input.
This procedure produces one data set per system response which describes the relationship of the response, the design parameters and the user input in a discrete representation. Based on this data an analytical response surface model is created which in turn establishes a continuous relationship between the responses, the design parameters and the user input. The relationship is established by the following equation representing a full quadratic model [10]:

$$y_i = \beta_{i0} + \sum_{j=1}^{m} \beta_{ij} x_{ij} + \sum_{j=1}^{m} \beta_{ijj} x_{ij}^2 + \sum_{k=1}^{m} \sum_{j=k+1}^{m} \beta_{ijk} x_{ij} x_{ik} + \varepsilon_i \qquad (1)$$

y_i *system response,* β_{ijk} *RSM coefficients,* x_{ijk} *design parameter,* ε_i *error estimator*

In order to obtain the actual RSM metamodel from the data previously generated by the numerical simulations, the problem specific RSM coefficients β_i have to be calculated using nonlinear regression. For this purpose the MATLAB Statistics Toolbox offers a suitable tool called *regstats*. It reads both, the results (system responses) of the numerical simulations as well as the samples (design parameters, user input) which were used as an input for the simulations. The RSM coefficients are exported into a matrix which serves as a working basis for the real time simulation system described in section 3.3.
Due to its simple algebraic structure the RSM can be evaluated very fast. Thus it is suitable for our purpose to perform a real time simulation of system responses. Of course the RSM has to be considered as an approximation method. Therefore its suitability and accuracy has to be considered.

3.3 Simulation System

The topology of the real time simulation system is shown in *Figure 3*. The system consists of three components: the RSM-based simulator is a software component that reproduces the physical behavior of the product. It uses the RSM metamodel generated during the model preparation process and calculates the system responses depending on the user input and given values of the design parameters in real time. The emulation of the human-machine interface is encapsulated into another software component. It can be considered as an adaptor between the haptic device and the RSM-based simulator. On the one hand it controls the haptic device to behave like the human-machine interface on the other hand it passes user input to the RSM-based simulator and in turn sends the system response from the simulator to the haptic device. Finally there is a stereoscopic graphics system that visualizes the product model including some of the system responses within a 3D virtual environment.

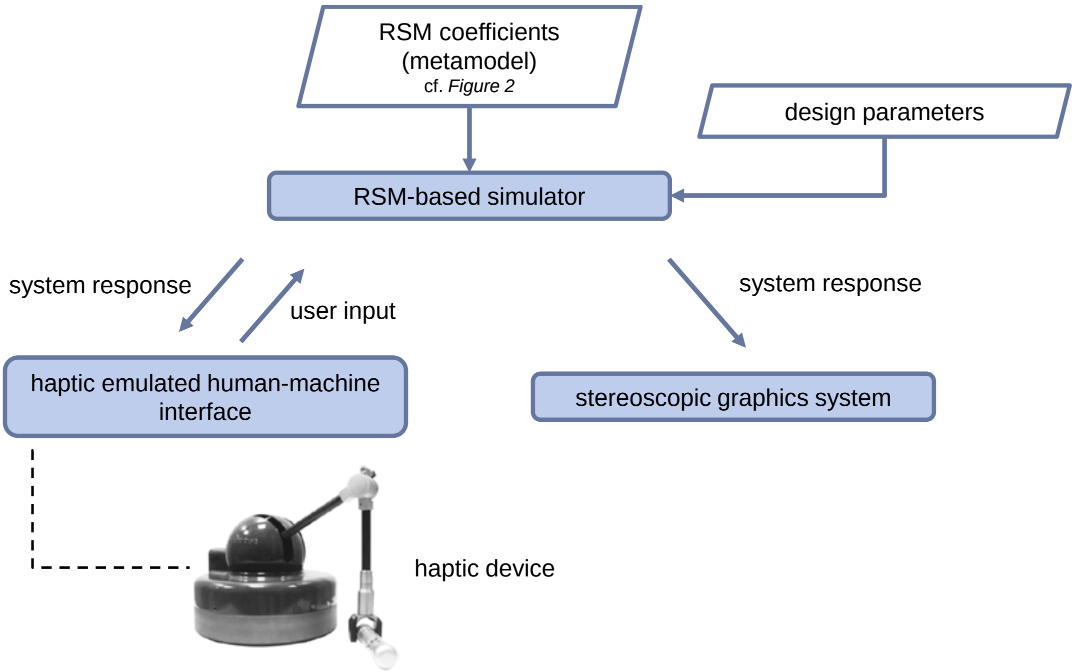

Figure 3. Topology of the simulation system

3.4 Emulation of the human-machine interface on a generic haptic device

The human-machine interface of a mechanical product may be composed of knobs, levers, sliders or cranks for instance. Each of these elements is characterized by a specific kinematic behavior. In this section an approach to emulate this behavior on a generic haptic device is presented.

As a haptic device Haption's Virtuose 3D-1525 (*Figure 4*) is used. The end effector can be moved around in six degrees of freedom. However force feedback is only generated for the three translational axes. A computer program can read information about the movement (position and speed) of the end effector from the device and send back information about forces to be applied to the end effector. The communication is done through an object oriented API implemented in C++ which is wrapped around hardware specific code.

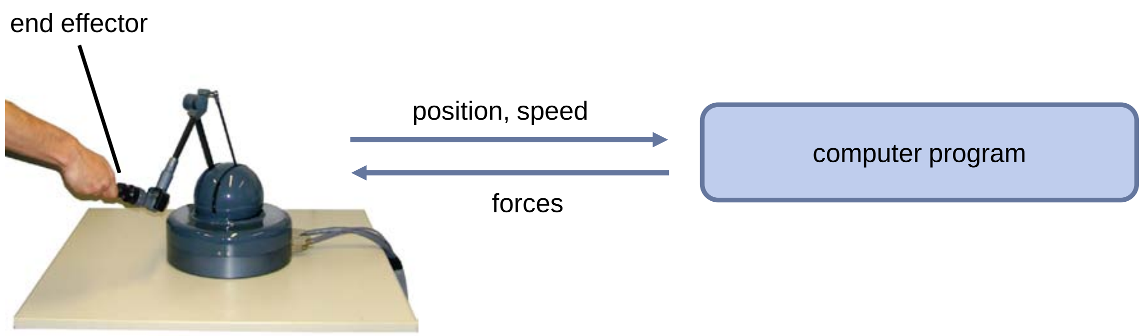

Figure 4. The haptic device and computer interface

In order to describe the movement of the end effector two right-handed coordinate systems are introduced. The inertial system I is located in the center base of the device with its axes oriented as depicted in *Figure 5*. A second, moving system E is fixed to the end effector. Thus the movement of the end effector with respect to the inertial system can be expressed by the following mathematical entities:

- Vector $\vec{x}_I$ (position)
- Quaternion q_I (orientation)
- Vector $\vec{v}_I$ (linear velocity)
- Vector $\vec{\omega}_I$ (angular velocity)

Forces acting on the end effector are described by a vector $\vec{f}_I$ with respect to the inertial system.

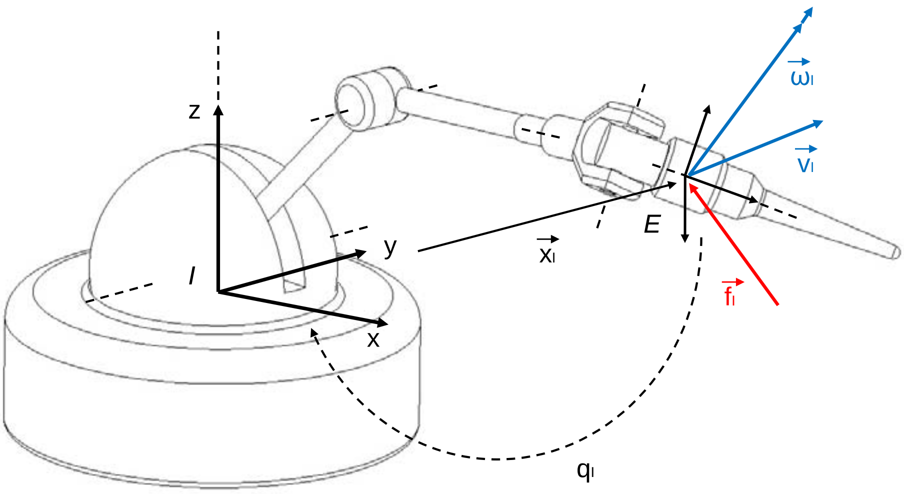

Figure 5. Mathematical entities on the haptic device

To emulate a certain kinematic behavior, the movement of the end effector has to be constrained in a suitable way. The fundamental algorithm to achieve this is shown in *Figure 6*. After the actual position and the actual speed of the end effector has been read from the haptic device, a desired position and a desired speed is computed based on an underlying kinematic model. Next, a compensation force is computed that pushes the end effector towards the desired motion when applied to the haptic device. This algorithm has to be iteratively carried out with a high frequency of about 1000 Hz. Due to the highly delicate human sense of touch [3], the user will perceive a buckling in the movement at lower rates.

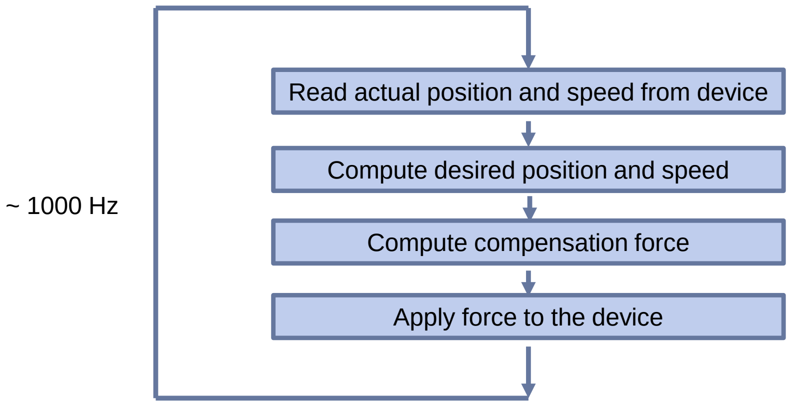

Figure 6. The emulation algorithm

For the sake of clearness the emulation algorithm is illustrated for a mechanical crank as a demonstrator, but the overall methodology can easily be transferred to other kinematics. For the emulation of a crank as shown in *Figure 7* the end effector of the haptic device can be identified as the handle. Consequently it has to be assured that the coordinate system E solely moves on a circular path. Additionally it should be possible to apply a torque M to the emulated crank that can be sensed by the user who holds the end effector in his hand. Further the crank angle φ and its angular velocity ω should be computed. The circular path is defined by an axis and the radius r. The axis in turn is defined by its origin $\vec{o}_I$ and direction $\vec{d}_I$. At this point it is necessary to introduce a third coordinate system C, which is located in $\vec{o}_I$ with its x-axis collinear to $\vec{d}_I$ and express all entities involved in the description of the device's movement with respect to C.

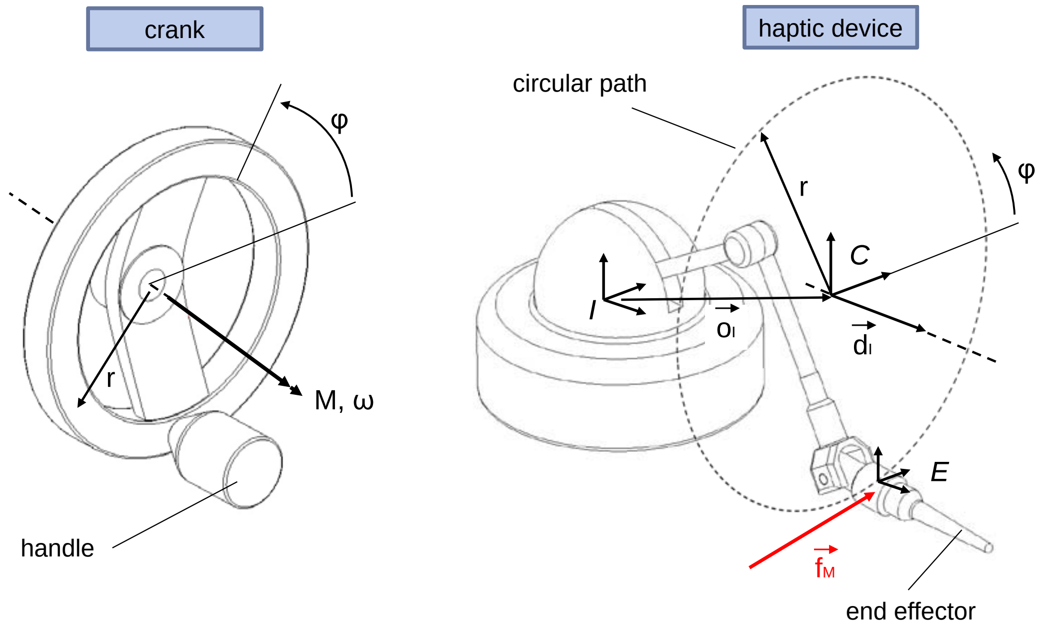

Figure 7. Emulation of a mechanical crank

In *Figure 8* $\vec{x}_C$ and $\vec{v}_C$ refer to the actual position and speed of the end effector expressed with respect to coordinate system C. In general, the end effector frame will not be located on the circular path.

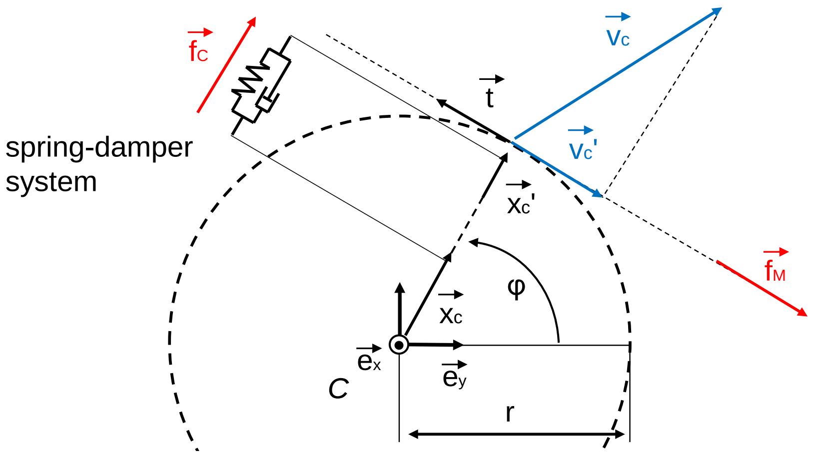

Figure 8. Positions, velocities and forces in the plane of the circular path

The desired position on the circular path $\vec{x}_C'$ is computed by projecting the vector $\vec{x}_C$ into the plane that is defined by the circular path setting the x-component of $\vec{x}_C$ to zero and subsequently scaling its length to match the radius r:

$$\vec{x}_C' = \begin{pmatrix} 0 & x_{Cy} & x_{Cz} \end{pmatrix} \frac{r}{\left| \begin{pmatrix} 0 & x_{Cy} & x_{Cz} \end{pmatrix} \right|} \tag{2}$$

If the movement of the end effector is constrained to a circular path, its velocity has to be tangential to the path. Thus the desired velocity $\vec{v}_C'$ is given by the tangential projection of the actual velocity $\vec{v}_C$ on the circle in the current position:

$$\vec{t} = \frac{\vec{e}_x \times \vec{x}_C'}{\left| \vec{x}_C' \right|} \tag{3}$$

$$\vec{v}_C{}' = (\vec{v}_C \cdot \vec{t})\,\vec{t} \tag{4}$$

The compensation force $\vec{f}_C$ which is necessary to drive the actual movement towards the desired movement is acquired by virtually connecting $\vec{x}_C$, $\vec{x}_C{}'$, $\vec{v}_C$ and $\vec{v}_C{}'$ using a spatial spring-damper system, which produces a force that is proportional to the difference between the actual movement of the end effector and its desired movement [7].

A torque M acting on the rotational axis of the crank results in a force $\vec{f}_M$ on the handle that can be perceived by the user. As shown in *Figure 6* the force is always tangential to the circular path and can be calculated as follows:

$$\vec{f}_M = \frac{M}{r}\vec{t} \tag{5}$$

The total force that has to be applied to the end effector is the vector sum of $\vec{f}_C$ and $\vec{f}_M$. Before the force can be sent to the haptic device it has to be retransformed into the inertial coordinate system I.

Finally, the current values for the angular velocity and the crank angle with respect to the coordinate unity vector $\vec{e}_y$ of system C have to be calculated:

$$\omega = \frac{\vec{v}_C{}'}{r} \tag{6}$$

$$\begin{aligned} cp &= \frac{\vec{x}_C{}'}{|\vec{x}_C{}'|}\cdot\vec{e}_y \quad \Rightarrow \\ \varphi &= \begin{cases} \arccos(cp) & if\ cp \geq 0 \\ \arccos(-cp)+\pi & if\ cp < 0 \end{cases} \end{aligned} \tag{7}$$

The emulation of the crank is implemented in a C++ class. On the one hand it communicates with the haptic device on the other hand it provides an interface to the RSM-based simulator. Thus the simulator can request the actual crank angle and angular velocity as a user input and apply a torque to the crank axis as a system response.

4. CASE STUDY: CAR JACK

4.1 The Car Jack

The objective of this case study is to demonstrate the relevance of the presented ***Hybrid Mock-Up*** approach for the design of mechanical products with a special focus on usability and ergonomic properties. The product to be designed is a mechanical car jack which is used in case of having a flat tire. The car jack (*Figure 9*) consists of an interface to the car (1) and a crank handle (2), which is regarded as the human-machine interface of the product. Force is applied to the handle by the user. The resulting torque is transmitted to a gear pair (3) via a shaft. The gear (3) drives a spindle (4) which is employed to move the car interface up- and down. All the components are assembled to a car jack body (5) which rests on the floor during use.

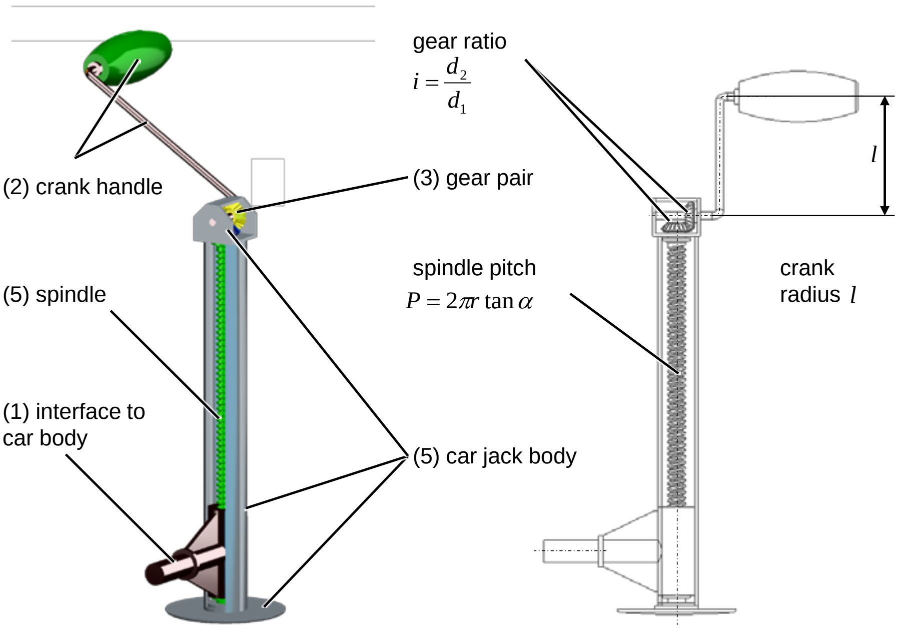

Figure 9. The Car jack and its crucial design parameters

Since car jacks are also used by unexperienced persons the ergonomic properties have to be considered as an important requirement for the product. In this context one aspect of usability is the effort the user has to accomplish at the crank in order to lift up his car. On the one hand it is desirable to minimize the force to be applied to the crank handle on the other hand it should be possible to lift up the car as quickly as possible. It is evident that these goals are contradictorily influenced by the following geometric design parameters: the spindle pitch, the gear ratio and the crank radius. (*Figure 9*) The problem for the designer is to find a combination out of these parameters which results in an operational comfort accepted by the majority of the prospected users.

4.2 Design space exploration

To solve the contradiction mentioned in the previous section and optimize the ergonomic properties of the car jack a design space exploration [9] is carried out. The design space for the car jack is spanned by the ranges of the geometric design parameters as shown in *Table 1*. The objective is to find a point in parameter space which results in an optimal design. Because the criterion for this optimization (good operational comfort) is highly subjective the prospected user of the car jack has to be involved into this process. Therefore the ***Hybrid Mock-Up*** approach presented above is chosen. It allows the user (represented by various test persons) to subjectively identify a good design.

Table 1: Variation ranges of the design parameters

Parameter	Minimum value	Maximum value
Crank radius (in mm)	50.0	190.0
Gear ratio (in -)	1.0	2.0
Pitch of the spindle (in mm)	2.0	10.0

4.3 Description of the Hybrid Mock-Up simulation system

The CAD-system PTC Creo Elements/Pro was used to set up a digital product model of the car jack. By carrying out a numerical multibody analysis with the mechanism module of PTC Creo Elements/Pro, two system responses to the user input (movement of the crank) were obtained in dependence on the design parameters: the resulting maximum torque on the crank shaft varies between 350 Nmm and 3900 Nmm (*Figure 10a*). The gradient of the torque curve rises if the pitch angle is increased. Consequently the number of rotations needed to fully lift the car decreases. This also means that the time to lift the car decreases (*Figure 10b*). The graph in *Figure 10a* also reveals that a nonlinear system behavior is present. The cause of this system behavior can be traced back to the process lifting the car: the gravitational force of the car body is not acting on the pin of the interface until lifting starts. Moreover the reaction force on the pin increases, the more the four springs of the car’s suspension system are unloaded. The springs feature a progressive characteristic curve. As soon as the wheel is fully lifted off the ground the reaction force and the torque stay constant (*Figure 10a*) while the lift position remains linearly increasing to its maximum.

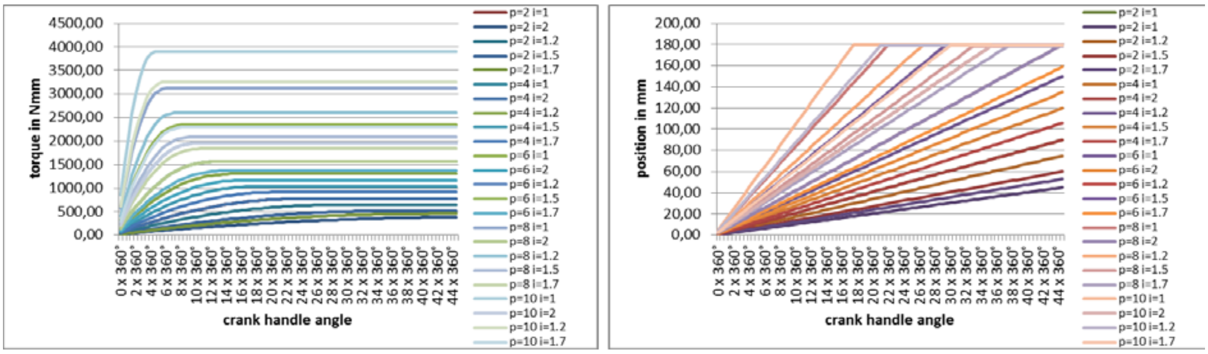

Figure 10. System responses: a) torque (left) and b) position of the car (right)

The results of the numerical simulations were exported in a comma-separated file format for further processing in MATLAB, which was used to obtain the regression coefficients of a full quadratic response surface metamodel. The software system that controls the haptic device loads a file containing the matrix of regression coefficients obtained from MATLAB and performs an evaluation of the system behavior function in real time.

The system response *position of the car* is visualized by a stereographic graphics system based on OpenGL whereas the force necessary to operate the car jack (resulting from the system response *torque*) is perceived by the test person through the haptic device. In order to identify the point in the design space which leads to the subjectively best operational comfort, the test person can interactively alter the values for the design parameters in the simulation software.

In this way the work methodology explained above in this paper has been exerted for the car jack in order to provide system ready for use. (*Figure 11*)

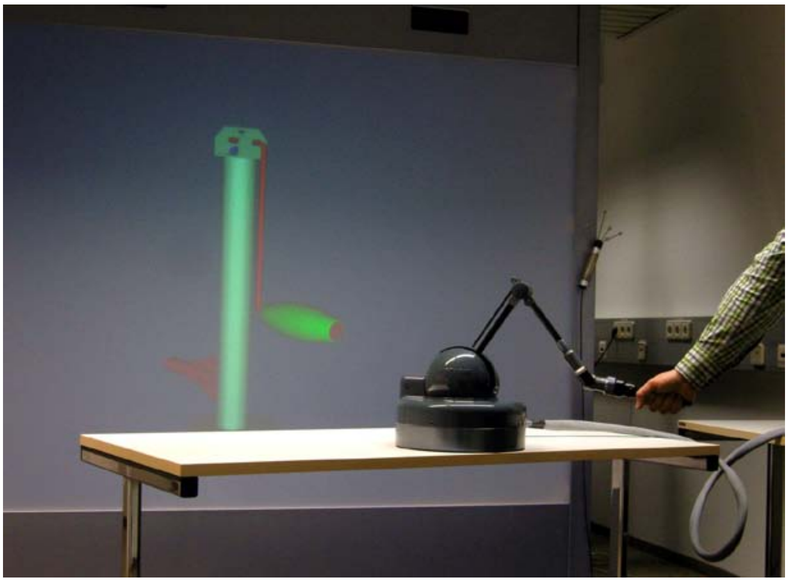

Figure 11. The Hybrid Mock-Up of the car jack running inside a VR-System

4.4 Evaluation of the approach

Initial tests with the simulation system have revealed that the haptic feeling operating the ***Hybrid Mock-Up*** of the car jack can be considered as very realistic. However the maximum force the present haptic device can produce is limited to 35 N. This means the maximum torque one can apply to the crank is also limited. This limit was reached at higher spindle pitches of about 9 mm. In order to simulate systems that exert higher working loads to the user stronger haptic devices have to be utilized. The ***Hybrid Mock-Up*** of the car jack has also been presented to the public within an academic fair at the University of Erlangen-Nuremberg in early 2011. About 20 persons were able to test the system. Even though the feedback of these test persons has not been evaluated statistically, some interesting observations have been made.

During the tests the persons were able to tune the design parameters in order to find a good combination. It became clear that most people preferred a combination of design parameters that is near a value of 6 mm for the spindle pitch, 150 mm for the crank radius and 1.5 for the gear ratio.

Moreover one person noticed that in the simulation the sense of rotation necessary to lift the car up was counter clockwise whereas out of the experience of that person most real car jacks go up when the crank is turned clockwise. Even though this example is quite trivial, it points out the ability of the ***Hybrid Mock-Up*** approach to reveal design faults.

All in all the simulation system worked out really well for most of the visitors of the fair. However some persons were not able to operate the virtual car jack without further advice. Most of them just didn't recognize the haptic device as a crank. Obviously there was a discrepancy between the visual appearance of the mock-up and its behavior. A possible reason is that at the fair the graphics system was running on a standard PC monitor. There was no stereoscopic graphics output even though the visualization component of the simulation software has suitable capabilities. For a tighter integration of the visual appearance and the haptic behavior it is necessary to integrate the simulation system into an immersive virtual environment. In such a VR-system the shape of the product is presented to the user as 3D stereoscopic graphics. In conjunction with the haptic device the overall product experience can be very realistic for the user.

5. CONCLUSION AN OUTLOOK

For the purpose of concept evaluation and design exploration within a human-centered design process, real touchable prototypes are often indispensible. This applies especially for products with human-machine interfaces consisting of mechanical elements. However the production of physical prototypes entails immense expenses of cost and time which leads to long iteration loops within the product development. In this paper a ***Hybrid Mock-Up*** approach was presented that allows a physical interaction with virtual prototypes. The behavior of the product is simulated digitally whereas elements of the human-machine interface are emulated using a generic haptic device. The benefit of the approach is that for the user a realistic product perception is achieved without having to dispense with the advantages digital engineering offers: saving of costs and time due to a reduction of physical prototypes and the possibility to carry out design changes very quickly.

It was shown how the behavior of mechanical components can be emulated using a generic haptic device. Response surface based metamodels [10] were used to meet the real time requirements of a computer haptic system. This approach allows the utilization of numerical simulation of arbitrary complexity to simulate the physical behavior of a product. In a case study the proposed work methodology was exerted to a crank driven car jack assembly. The ***Hybrid Mock-Up*** simulation system was used to find a suitable combination of geometrical design parameters so that the ergonomic properties of the jack subjectively perceived by the user are optimal.

Due to its relatively simple structure, the behavior of the demonstrator could have been described using solely analytical equations. Nevertheless numerical simulations in combination of RSM metamodels were chosen in order to outline the generality of the approach. However for a range of simple systems analytical simulation procedures may be suitable and should be considered because the tedious pre-calculation process is avoided. Future work will aim at a modular simulation environment for the behavioral simulation of mechanical systems. Both, analytical and numerical simulation technologies will be used in combination. Moreover methodologies for taking into account disturbances caused by manufacturing discrepancies have to be developed. With such a system it would become possible to accomplish tolerance analyses with user-related key characteristics. In many applications this is an issue which is often disregarded. But deviations (e.g. caused by manufacturing deviations) influence product behavior and its perception a lot. Therefore it is an essential task to virtually provide tolerance information for use with haptic devices to improve the ***Hybrid Mock-Up***.

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