Haptic Rendering of Actuated Mechanisms by Active Admittance Control

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Abstract. Virtual Prototyping with haptic feedback offers great benefits in the development process of actuated systems. We present a generic control scheme for the haptic rendering of actuated mechanisms, introducing the *active admittance*. It extends the conventional admittance control by modeling the actuation and the movable parts of the mechanism separately. This allows for an efficient iterative design and evaluation of an actuated mechanism and its single elements. The practicability of active admittance control is demonstrated by haptically rendering a car door with two actuated degrees-of-freedom.

Key words: virtual prototyping, haptic rendering, admittance control, active admittance, sensors, actuators, mechanism, stability

1 Introduction

The conventional product development process for actuated, in particular mechatronic systems, with their "Build - Test - Refine" cycles requires the use of hardware-based mock-ups to evaluate the proposed system design[1]. Based on the evaluation results, potential for improvement of basic elements, subsystems or the overall system can be recognized and then realized in the next iteration of the product design.

The construction of a physical mock-up is usually very time consuming, expensive and prone to errors. This holds especially for complex mechatronic systems which feature a lot of interdependencies between their mechanical, electrical and electronic components. So, the use of virtual rather than physical mock-ups for the validation of functionalities and properties of mechatronic systems has been the preferred choice[2] [2].

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[1] Compare for example the design guideline VDI 2206 [1] for mechatronic systems, which introduces the concept of iterating "macro cycles", each including the construction of a hardware prototype as an intermediate result.

[2] The rise of Rapid Prototyping of physical parts does not contradict this statement, because the main problem of building a physical prototype of a mechatronic system is to design and connect its individual, interdepending parts in such a way that the resulting behavior of the system is adequately displayed. This is often very complex.

The use of virtual mock-ups is known as Virtual Prototyping (VP). In VP, the user interface can feature a combination of different modalities. As noted in [3], one major advantage of haptically-enhanced VP is that even in the early stages of design, comparative and repeatable user tests can be performed.

In the field of haptic rendering of actuated mechanisms, little research has been carried out. Our contribution is a generic, straight-forward admittance control scheme for the haptic rendering of such mechanisms. The core of it is the *active admittance*, a model that comprises all elements of the actuated mechanism that contribute to its haptic behavior. This allows for an efficient development of the mechanism and its individual parts. As an application of this approach a car door example is presented.

2 State of the Art

A variety of methods for the control of haptic devices have been proposed. Well-known methods are the impedance and admittance control schemes. Admittance control masks the natural dynamics of haptic devices to the user. It is therefore often the preferred choice, especially when large mechanisms are to be rendered. Additionally, it is the most intuitive way of simulating the dynamics of a mechanism, because the user interaction wrench w_H (= forces/torques) results in a motion of the robot that is equivalent to the motion a physical instance of this mechanism would exhibit [4]. The virtual mechanism is simulated by applying the measured user interaction w_{HM} to its equations of motion (“admittance”,”virtual environment”). This yields the motion of the simulated mechanism, which is haptically displayed to the user e.g. by a position-controlled robot, see Fig. 1. To improve the haptic rendering, the violation of kinematic constraints can additionally be fed forward [3].

Alhough several methods for the haptic rendering of mechanisms have been proposed, to the knowledge of the authors, there are no haptic control schemes which explicitly take into account the actuation of a mechanism[3]. “Actuation” is used here as an umbrella term for the entirety of all elements that have to do with creating actuator forces/torques w_A. For a realistic rendering it is critical to identify and model the elements that have a significant influence on the actuation and thereby on the haptic behavior of the actuated mechanism.

A lot of research has been carried out to examine the influence of the hardware and the control law of haptic devices on the stability of haptic rendering, see [6, 7]. Most of it considers the admittance to be a linear, time-invariant set of differential equations. An extension to nonlinear virtual environments can e.g. be found in [8]. However, no control scheme is known to the authors that can efficiently be used to model and haptically render an actuated mechanism with its distinct elements. By presenting the method of *active admittance control*, we bridge this gap.

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[3] Outside the realm of haptic rendering, the simulation of actuated mechanisms has long been studied [5].

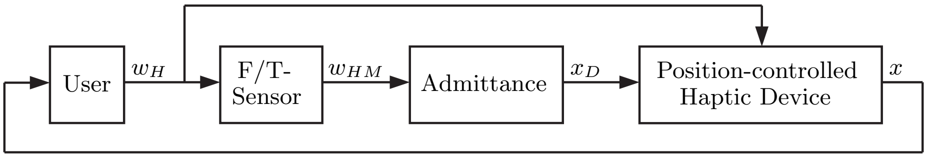

Fig. 1. Conventional admittance control scheme (w_H/w_{HM}: actual/measured user wrench, x/x_D: actual/desired Cartesian position and orientation)

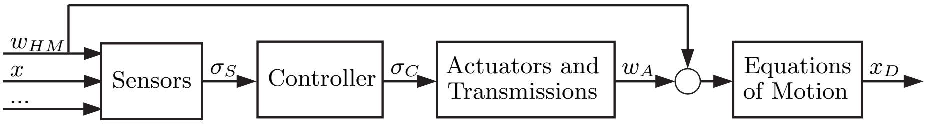

Fig. 2. Active admittance: An actuation model calculates the actuation wrench w_A, which acts in addition to the user wrench w_{HM} on the mechanism.

3 Active Admittance Control

The main components of a mechanism "actuation loop" typically are:

1. Sensors
2. Controller and I/O-Interfaces
3. Power electronics
4. Power supply
5. Actuators
6. Transmissions
7. Movable parts of the mechanism

All of these components contribute to a different extent to the haptic behavior of the mechanism. Especially when being in an early stage of product development, not the least detail may have to be modeled accurately. So, only the component individual properties that have a significant influence on the haptic behavior may have to be modeled. For instance, in many cases the (slow) dynamics of the actuators dominate the overall dynamic, while the time consumption of the data acquisition, the signal processing and the power electronics may be negligible. Furthermore, the power supply can often be regarded as ideal. For sake of simplicity, we neglect the elasticity of parts of the mechanism. These considerations lead to a simplified model of the actuation, see Fig. 2.

Sensors: Some of the sensor signals σ_S that are input for the controller may be derived from real sensors that are already part of the haptic interface or can be combined with it, e.g. position or force sensors. They are transform with respect to resolution etc. The other sensor signals have to be completely simulated.

Controller and I/O-Interfaces: The control scheme of the actuated mechanism can usually be modeled very easily, as it usually already is a mathematical expression. The interfacing electronics have to be modeled accurately to preserve their unfavorable influence on the haptic rendering.

Actuators and Transmissions: Besides an accurate model of the dynamics of the actuators, a model of unfavorable effects like backlash, friction etc. may be of particular interest.

As the most relevant elements of the actuation have been modeled, the actuation wrench w_A can be calculated. It is acting in parallel with w_{HM} on the mechanical parts of the simulated mechanism, which can be described by its equations of motion. In analogy to conventional admittance control, this results in a simulated motion x_D.

The resulting structure can be seen from Fig. 2. We term this model an *active admittance*, because in addition to sources of instability ("energy leaks") that admittance implementations in general exhibit, it can increase the energy of the overall haptic control system by applying a dedicated actuation wrench. For example, if one task of the controller was to prevent the door from colliding with other objects, the controller would calculate a wrench counteracting such a collision. This could increase the velocity of mechanical parts of the system, and thereby modify the kinetic energy of the overall system.

At first sight, one might argue that there is no big difference in adding an additional term w_A to the user interaction w_{HM} before applying it to a conventional admittance in terms of stability. Unfortunately, this does not hold true in general: Given a simulation that contains a very dynamical and/or powerful actuator and a suitable controller, the bandwidth and/or the magnitude of w_A can be dominating over any possible excitation by a human.

In the past, passivity-based control schemes for a stable haptic rendering of even nonpassive virtual environments have been proposed [8, 9]. The use of such schemes could be useful as a safety measure when rendering actuated mechanisms. Though, the problem is that the additional control action which is triggered by such a scheme would lead to an adulteration of w_A and thereby of the haptic rendering. A solution could be to include e.g. a passivity controller in the control law of the actuated mechanism itself so that a w_A is ensured which cannot induce instability in the overall haptic rendering.

However, a detailed discussion of the stability of active admittance control is beyond the scope of this paper. Thus, for now we state that the design of an active admittance that renders a mechanism and its actuation with high quality while guaranteeing stability of haptic rendering is an open problem.

4 Application to a Novel Car Door

The active admittance control scheme in combination with the haptic device ViSHaRD10 [10] has been used to evaluate a novel car door, the Actuated Pivotable Sliding Car Door (APSCD). This door concept is expected to be desirable for car drivers as it combines the convenience of a sliding door with the general customer acceptance of a swing door.

The proposed APSCD consists of an actuated slider (Link A) on which an actuated "conventional" car door (Link B) is mounted, see Fig. 3. Thus, the system can be described by the generalized coordinates x and ϕ. To keep the example simple, only the outer door handle is used as an interaction port. Thus, the location of HIP in Fig. 3 determines the mapping of the external user wrench $w_H = (f_{I_x}, f_{I_y}, \tau_{I_z})^T$ into the mechanism space given by x and ϕ.

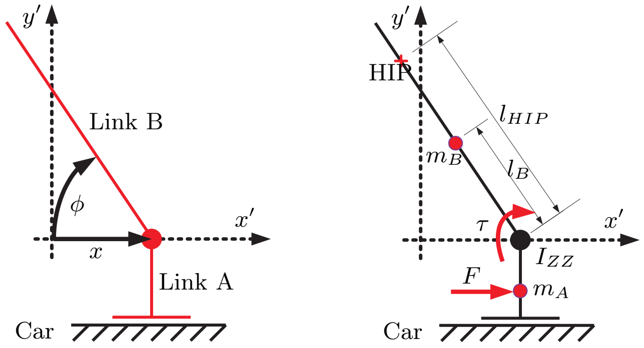

Fig. 3. Sketch of the Actuated Pivotable Sliding Car Door (APSCD)

Table 1. Parameters of the simulated APSCD

m_A $[kg]$	m_B $[kg]$	I_{ZZ} $\left[\frac{kg}{m^2}\right]$	l_{IP} $[m]$	l_B $[m]$	μ_A $\left[\frac{Ns}{m}\right]$	μ_B $\left[\frac{Ns}{rad}\right]$	T_A $[ms]$	T_B $[ms]$
6.0	24	3.2	1.2	0.58	1.5	2.5	4.0	5.0

A simple control law has been chosen to represent the controller. It is designed to react with a predefined f_{CA} / τ_{CB} if an upper or lower border of the variable x / ϕ is violated. Thereby, a collision between the car door and the car bodywork can be prevented. DC drives with time constants T_A and T_B have been chosen as actuators. For lack of space, we assume here that the dimensionless transfer function of the encoders, the power electronics and the transmissions equals 1. Further, we assume that the friction effects of both joints are dominated by Coulombian friction which can be described by the coefficients μ_A and μ_B. The equations of motion of the APSCD are given below.

$$\begin{pmatrix} m_A + m_B & m_B l_B \sin\phi \\ m_B l_B \sin\phi & m_B l_B^2 + I_{Bzz} \end{pmatrix} \begin{pmatrix} \ddot{x} \\ \ddot{\phi} \end{pmatrix} + \begin{pmatrix} \mu_A \dot{x} \; + m_B l_B \cos\phi \, \dot{\phi}^2 \\ \mu_B \dot{\phi} \end{pmatrix} = \begin{pmatrix} f_A + f_{I_x} \\ \tau_B + \tau_{I_z} + l_{IP}(f_{I_x} \sin\phi + f_{I_y} \cos\phi) \end{pmatrix} \qquad (1)$$

Solving these equations for x and ϕ, the simulated states (x, ϕ) of the mechanism can be calculated. Finally, these states are mapped to the joint space of ViSHaRD10 and fed to its position controller.

The implementation of an active admittance representing the APSCD turned out to be straightforward. Some preliminary experiments have been conducted using the parameters noted in Table 1. Both the kinematic and dynamic properties were displayed correctly, and the simulated controller effectively prevented a violation of the predefined joint limits. During the evaluation of the APSCD, the coupling between the two DOFs which can be seen from (1) posed a problem: Users were not able to fully anticipate the behavior of the car door. Thus, an assistance function should be developed to improve the usability of the car door.

5 Conclusion

Conventionally in haptic rendering, admittances are used which represent mechanical mass-spring-damper systems without consideration of actuation. We propose an extended admittance model, the *active admittance*. It includes models of all significant elements of the actuation loop, particularly the sensors, the controller, the actuators and the transmission. Based on this, the actuation wrench (forces and torques of the actuators of the mechanism) can be calculated. Both the actuation and the user wrench act on a mechanical model which is given in generalized coordinates. This leads to motion of the simulated mechanism that can be displayed by a haptic device. The active admittance control has successfully been used to render an actuated car door with two DOFs.

Future work involves the design of a control paradigm for active admittance control that guarantees stable haptic rendering.

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