2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Robust Control of Interaction with Haptic Interfaces

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Abstract— **The primary concern in haptic systems is to achieve stable interaction under any operating conditions and for all simulated virtual environments, without unwanted oscillations that degrade virtual surface rendering.This paper represents a novel approach for controlling interaction with a haptic interface based on robust control design framework established for the control synthesis of interaction between an impedance-controlled robot and a passive environment. Initial experiments results have demonstrated advantages, high performance in interaction with a very stiff environment and reliability of the new algorithms.**

I. INTRODUCTION

Recently, outstanding research interest addresses new interactive systems designed for interaction between human and a robotic device, or with remote or virtual dynamic environments. To new interactive systems belong kinesthetic displays and haptic interfaces, teleoperation systems, human enhancers and augmentation devices, etc. These systems are designed to produce/receive kinesthetic stimuli for/from human movements, as well as to render a realistic feeling of contact and dynamic interaction with nearby, remote or virtual environments. The advanced interaction systems have recently found very attractive applications in surgical and rehabilitation robotics, power assist-devices, training simulation systems, etc. The most critical issue in these systems is to ensure stable and safe interaction with a high rendering performance. This is a challenging task, when taking into account serious problems, such as unknown and variable human dynamics, commonly non-linear environmental characteristics, as well as various disturbances in computer-controlled systems.

Numerous experiments clearly demonstrate that the contact stabilization with stiff, delayed and non-linear environments still represents the crucial problem in haptic interfaces. The specific problem in haptic interfaces is lack of objective stability testing. Human exhibits good capability to stabilize (damp) the interaction with a slightly oscillating environment. Therefore, the lost of contact and bouncing in haptic interfaces appear to be less critical [1], comparing with contact stability problems in industrial robots investigated in [2, 3]. However, these oscillations can jeopardize interaction fidelity. In majority of experiments the increasing of sampling rates and reducing of force magnitudes have been recognized as promising measures to reduce bouncing.

The synthesis of robust control laws has been confirmed in [2-4] to be very efficient for stabilization of interaction between a robot and a stiff and force-delayed environment taking into account desired interaction performance. Testing this approach in various robotic systems has demonstrated the feasibility and reliability of the interaction control approach even for relative higher control rates and lags. Robust stability provides useful design tools for control synthesis for linear and non-linear systems. Therefore, it is promising to apply established robust control for haptic system design. This paper present the extension new robust control design framework established for the control synthesis of interaction between an impedance-controlled robot and a passive environment to other interactive systems with physical or virtual interfaces. The application of robust contact control is possible for both basic haptic interaction systems: *admittance* and *impedance displays*, however due to limited space only admittance displays will be considered.

II. HAPTIC SYSTEM STRUCTURES

Although study and modeling of human motor control and spatial limbs dynamics are fundamental challenges in biomechanics and neuroscience, the understanding of human interaction with a dynamic environment is still insufficient. The key quantity describing human arm dynamic interaction is the end-point impedance [5]. Numerous studies have recently demonstrated surprising human capabilities to adapt the arm impedance to variable interaction conditions and perturbations [6], even so to perform mechanically unstable tasks [7]. The Cartesian end-point arm impedance is non-linear and non-symmetric spatial impedance combining passive and active components [5]. However, in the control analysis human impedance is commonly, for the sake of simplicity, considered as linear variable impedance, often with one or two DOF's. Likewise, the haptic display dynamics can be considered as a linear admittance, while the environment generally can be represented by non-linear impedance.

Essentially the basic interaction chain in a haptic display consists of three principal elements (Fig. 1): human operator (H), haptic device (D) and virtual environment (VE). The middle element in this model is a haptic device, which is, based on analogy with electrical network circuits, represented as so-called *two-port network.* A haptic device interconnects the human with the virtual environments (both linked as *one-port networks*) via force and velocity I/O signal pairs, describing the exchange of energy between blocks This representation has been demonstrated to be very useful in analysis of tele-operation and haptic systems [8, 9]. Since the haptic device is computer controlled, critical sampled-data (SD) effects on interaction system stability (e.g. control delay and sample-and-hold effects) must be also introduced in the interaction model. The main role of SD control system is to measure and render I/O signals via the haptic interface, and thus to provide the operator with an enforced sense of haptic (or kinesthetic) presence in a virtual environment.

However, the performance obtained with the basic interaction system is commonly poor and therefore such an interaction structure is not feasible. Generally it is not possible to guarantee the stability of interaction with the simple haptic interface control system. In order to simplify design and to improve the stability of the haptic interaction system, Colgate *et al.* [10] have proposed to couple an additional block, referred to as *virtual compliance* or *virtual coupling* (Fig. 1), between the haptic device and the virtual environment. The virtual coupling is commonly selected as impedance, i.e. the new block represents an admittance. The virtual coupling provides a simple, nevertheless stable and robust haptic controller. For a particular haptic device a corresponding virtual coupling might be designed regardless of simulated virtual worlds and real human behavior. The main design goal is to ensure passive behavior of the coupled subsystem consisting of the virtual coupling and the haptic display, thereby also taking into account critical SD effects (sampling and control delay). By these means, when taking into account that the human performs almost passive and stable interaction with a passive system, the stability of the entire haptic system may be ensured under all operating conditions if the virtual environment is passive.

The stability of the haptic interaction system is commonly considered based on the passivity theory. Colgate and Schenkel [11] have derived explicit conditions for the passivity of a haptic systems including a linear haptic device, a virtual coupling and a virtual environment, taking into account sampling and computation delay effects. The authors argued the essential relevance of physical damping parameters for enhancement of system passivity and interaction stability. For a simple SISO coupling system consisting of the haptic-device, i.e. admittance $\mathrm{Z_D} = 1/(\mathrm{ms} + \mathrm{b})$, and the virtual-coupling impedance $\mathrm{Z_V} = \mathrm{Bs} + \mathrm{K}$, the stability (passivity) condition imposes

$$\mathrm{b} > \frac{\mathrm{KT}}{2} + \mathrm{B}$$

where T is control sampling time. In this elemental case of a haptic interface, the virtual coupling represents a virtual wall, which consists of parallel connection of the virtual stiffness K and the virtual damping B, to be rendered to the human. Hence, the above condition means that a physical damping must be involved in the system in order to ensure a stable interaction with the virtual wall. Higher sampling rates (i.e. smaller T) facilitate the implementation of stiffer walls. Brown and Colgate [12] derived similar expressions for the minimum mass of the virtual wall that can be simulated passively. In the *natural admittance control* [13] maximum allowable mass ratios and stiffness of the interaction systems were determined to ensure passive interaction and stability.

However, the stability conditions that were obtained appear to be quite conservative, especially in admittance displays with high inherent inertia and control stiffness (e.g. industrial robots). An application of such systems requires high mass and stiffness ratios, which are difficult to achieve with established stability conditions. The criteria based on (1) imply physic-based system design that is not always reliable. For example, higher additional damping (1) allows higher virtual impedance to be realized, but thereby the impedance of the haptic device must also be increased.

Adams [14] has proposed an approach for a virtual coupling design based on the network stability that appears to be less conservative than the passivity based synthesis. The stability of two-port network consisting of the haptic device and the virtual coupling guarantees the stability of a haptic interface when coupled with any passive virtual environment and human operator. Miller *et al.* [1] have extended the passivity based approach to haptic systems involving non-linear and time-delayed virtual environments. Hannaford and Ryu [15] have applied time-domain passivity analysis in order to improve the system performance in contact with a very stiff and delayed environment.

Our goal in this paper is to establish more practical robust suitable for synthesis of admittance displays.

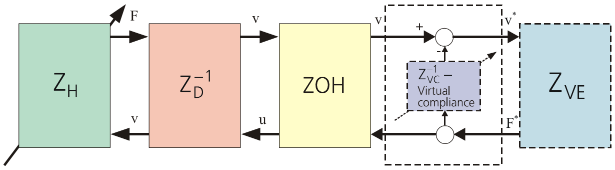

Figure 1. Elemental network model of a haptic system with virtual coupling (admittance)

III. ROBUST INTERACTION STABILITY

At first let us consider the interaction between a robot and a passive environment. A fundamental approach for controlling the interaction between the robot and the environment is based on the impedance control. The control objective of the impedance control differs from the conventional control goals in this sense that the main control issue is not to ensure tracking of a reference input signal (e.g. nominal position or force), rather to realize a reference target model specifying the interaction between robot and environment, i.e. the desired relationship between acting forces and robot motion reaction. The control input describing a desired target impedance relation may, in principle, have an arbitrary functional form, but it is commonly adopted in the linear second-order differential equation form (2), describing the simple and well-understood mass-spring-damper mechanical system

$$\mathrm{F} = \mathrm{M_t}(\ddot{\mathrm{x}} - \ddot{\mathrm{x}}_0) + \mathrm{B_t}(\dot{\mathrm{x}} - \dot{\mathrm{x}}_0) + \mathrm{K_t}(\mathrm{x} - \mathrm{x}_0) \qquad (1)$$

Where $\mathrm{x_0}$ is nominal robot position, $\mathbf{x}$ is the actual one, M_t, B_t and K_t are target mass, damping and stiffness respectively, F is the external force exerted upon the robot. Target impedance $Z_t = G_t(s)$ commonly relates force and velocity. However, in industrial robotic systems it is common to express the impedance in the above form relating forces and position deviations. For a SISO system $G_t(s) = M_t(s^2 + 2\xi_t\omega_t s + \omega_t^2)$.

Target impedance can be realized using various control techniques [2] (e.g. model-based computed torque control, position based compensation algorithms etc.). In the *impedance control*, contact stability issues have mainly been considered based on simplified models of interaction between a target impedance system and the environment. This approach, to be followed also in this paper, is correct, if we split the impedance control design task into two subtasks concerned with target model realization and target parameters design, respectively, assuming thereby that the target model can be realized relatively accurately. Several impedance control techniques have been developed to realize correctly a simple mass-damper-spring target model based on non-linear dynamic decoupling approach, or in industrial robots (with dominant diagonal and spatially round transfer matrices), based on linearized control laws [2]. Therefore, we will replace the robot with target impedance $Z_t = G_t(s)$ interacting with a environmental impedance $Z_e = G_e(s)$ (Fig. 2).

The following models describe the interaction in the coupled system on (Fig. 3). To become more realistic models, the force disturbance d_f is introduced representing unmodeled effects, sensory noise etc. Assume that the controlled robot-environment interaction can be described by the target impedance behavior (1)

$$F = \hat{G}_t(s = (x_0 - x) = \hat{G}_t(s)e$$

where $\hat{G}_t(s)$ is realized target impedance and e denotes position deviation caused by compliance effect (i.e. interaction force). Let consider the model of environment in the form

$$F = G_e(s)\ (x - x_e) = G_e(s)\ p = G_e(s)\ (p_0 - e) \qquad (2)$$

assuming that the environment is *passive,* where x_e denotes position of the environment, while p and p_0 represent penetration and "nominal penetration" into environment.

The *coupled impedance model* expresses the relationship between the interaction force F and nominal penetration $p_0 = x_0 - x_e$ (the real penetration is $p = x - x_e$), by means of the so called *contact impedance*

$$\begin{aligned} F(s) &= G_e(s)\left[I + \hat{G}_t^{-1}(s)G_e(s)\right]^{-1} p_0(s) = \\ &\left[I + G_e(s)\hat{G}_t^{-1}(s)\right]^{-1} G_e(s)p_0(s) \end{aligned} \qquad (3)$$

This model can be transformed to express the relationship between position deviation $e = x_0 - x = p_0 - p$ and nominal penetration *(deviation model)*

$$\begin{aligned} e(s) &= \hat{G}_t^{-1}(s)G_e(s)\left[I + \hat{G}_t^{-1}(s)G_e(s)\right]^{-1} p_0(s) = \\ &\left[I + G_e^{-1}(s)\hat{G}_t(s)\right]^{-1} p_0(s) \end{aligned} \qquad (4)$$

We are interested in the stability of the coupled interactive system described by the above linear models. The following theorems define the stability conditions during both transition and coupled interaction contact phases. Due to limited space, the stability will be considered in a simpler manner, more detailed considerations are given in [2]. Consider the interaction model on (Fig. 2) and assume that the achieved admittance can be represented as target one perturbed by a multiplicative perturbation

$$\hat{G}_t^{-1}(s) = (I + \Delta_t(s))G_t^{-1}(s) \qquad (5)$$

Conveniently, the perturbation can be presented in the form $\Delta_t(s) = \Delta(s)W_t(s)$ [16], where $W_t(s)$ is a fixed stable transfer function matrix, chosen as a diagonal stable, proper and minimum-phase transfer function matrix, and $\Delta(s)$ is a variable stable transfer function matrix satisfying $\left\|\Delta(s)\right\|_\infty \le 1$. Now, the following robust stability test can be introduced

Theorem 1 *(Robust coupled stability): A sufficient condition to guarantee that instability cannot occur for any possible allowable multiplicative perturbations of the target admittance satisfying* $\left\|\Delta(s)\right\|_\infty \le 1$ *, in contact with a passive stable environment is*

$$\left\|W_t(s)\left(I + G_e^{-1}(s)G_t(s)\right)^{-1}\right\|_\infty \le 1 \qquad (6)$$

Proof : It is based on generalized Nyquist theorem and due to limited space will be omitted (see [2] for details). The same relation will be proven below in a simpler way, considering robust contact transition stability.

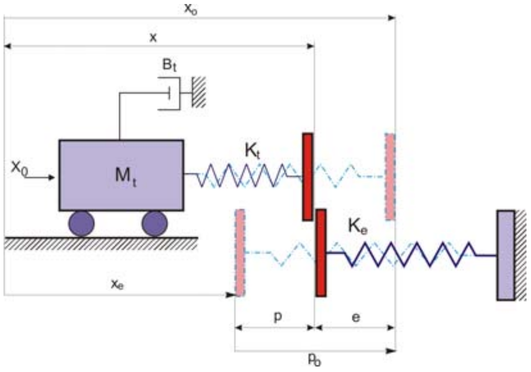

Figure 2. Basic "penetration model" of interaction with a passive environment

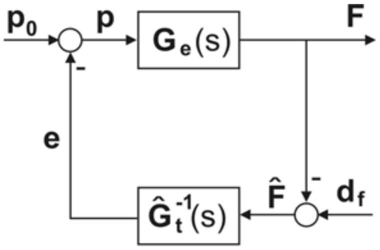

Figure 3. Interaction control model

Coupled stability assumes that the contact cannot be lost (bilateral contact). However in numerous experiments was demonstrated that the transition from free to constrained robot motion and contact losses represent critical issues. From a pragmatic viewpoint, the *contact transition* can be considered *stable*, if the contact is not lost after the manipulator hits the environment. A stable contact transition can be characterized by one of the following features: *non-zero force* (after contact is detected), *positive penetration* of manipulator end point into environment, *nonappearance of* *bumps*, etc. From (Fig. 2) it is obvious that a stable contact transition is characterized by

$$e(t) \le p_0(t) \tag{7}$$

In other words, this relation implies the actual end-effector position during a stable contact transition to always be located between the position of environment and the nominal position (Fig. 2). Since this contact stability condition is based on a simple geometric consideration it will be referred to as *geometric criterion*. The advantage of the geometric criterion is that it compares two time signals. For this purposes various norms can be applied. The norm comparison offers possibilities to apply relatively simple and efficient control techniques for the contact stability analysis. The usage of L_1 norms provides both necessary and sufficient conditions, however it is very difficult to transform these conditions in useful stability criteria in parametric space. As will be shown, this permits the second-norm. In that case, however, the condition (7) only ensures *sufficient* contact stability conditions, but not the *necessary* ones. Obviously, even when $\|e\| \le \|p_0\|$ is filled they may exist time intervals in which $e(t) > p_0(t)$. Consequently, the obtained contact stability indices might be conservative. However, in the control praxis it is common that when practical design-oriented conditions cannot be found, the control synthesis may be realized based on sufficient ones, of course, if they provide useful and experimentally proven solutions.

Theorem 2 *(Robust contact transition stability criterion): A sufficient condition for a stable contact transition of a linearized robotic control system under impedance control from the free space to an unilateral contact with any passive environment, is that 2-norm/2-norm system gain of the feedback system with the input-output pair* $\{p_0, e\}$*, i.e.* $\infty -$*norm of the corresponding transfer function matrix* $\left[I + G_e^{-1}(s)G_t(s)\right]^{-1}$*, is less than 1.*

Proof : It is based on the bounds upon 2-norm input/output gain [10]. In the considered case the relationship between nominal penetration and position deviation signals "energy" is limited by

$$\frac{\|e\|_2}{\|p_0\|_2} \le \left\| \left[I + G_e^{-1}(s)G_t(s)\right]^{-1} \right\|_\infty$$

A stable transition characterized by $e(t) \le p_0(t)$ imposes

$$\frac{\|e\|_2}{\|p_0\|_2} = \frac{\int_0^\infty e^2(t)dt}{\int_0^\infty p_0^{\,2}(t)dt} \le \left\| \left[I + G_e^{-1}(s)G_t(s)\right]^{-1} \right\|_\infty \le 1$$

Introducing the unstructured perturbations in the robot/environment interaction model and assuming the multiplicative uncertainties the above condition becomes

$$\frac{\|e\|_2}{\|p_0\|_2} \le \left\| W(s)\left[I + G_e^{-1}(s)G_t(s)\right]^{-1} \right\|_\infty \le 1 \tag{8}$$

The obtained contact transition stability condition is the same as previously in the Theorem 1 derived criterion for robust coupled stability (6). Practically the criterion (8) satisfies *both robust coupled and contact transition stability* and will be referred to as *general interaction stability criterion*.

H_∞ induced norm utilized in the above condition, describes maximum energy gain measure, and it is quite useful in analyzing the performance and synthesis of stable interacting impedance control systems. In linear systems the result of H_∞-norm based synthesis can be directly applied in both continuous and discrete time control. A common proximal method of converting a continuous (analog) system to a digital system with the same properties is based on the *bilinear transform*, a special case of which is *Tustin transform*. For the contact stability analysis also is relevant a key property of the Tustin transform that it *preserves* the H_∞ norm. Considering the correspondence between H_∞ norm and the passivity [2], Tustin's method is also a *passivity preserving* discretization technique. Hence, the results of stable interacting system synthesis in the continuous-domain can be applied in the discrete-time and vice versa. Assuming the dominant delay in the force feedback loop (Fig. 3), the stability condition (8) becomes

$$\left\| \left[I + z^n G_e(z)^{-1} \hat{G}_t(z)\right]^{-1} \right\|_\infty < 1 \tag{9}$$

where z is the delay operator for fixed sampling period and $\hat{G}_t(z)$ denotes realized target model. The generalized contact stability conditions (8-9) ensure both contact transition and coupled interaction system stability. Robust control provides an efficient framework for synthesis of the impedance controller in both continuous and sampled-data systems based on H_∞ norm. Rather than developing complex transition control algorithms, the main idea is to tune the target system parameters in order to meet both the interaction performance and the stability. Moreover, the condition (8) provides a control design-oriented approach. In a simple algorithm [2], we can assume an environment, choice some target impedance parameters (e.g. stiffness, based on estimated maximum forces and position deviations, i.e. penetrations into environment) and synthesize realizable remaining parameters ensuring the robust stability in spite of environmental uncertainties and presence of non-linear effects estimated by W(s). Thereby the delay effects, which are crucial for the stability, can also be taken into consideration (9). Therefore it is promising to apply the robust control approach for the design of the impedance control which is intended for the interaction of industrial robots with a passive or active environment (Fig. 4). This design-oriented criterion was in numerous applications in space and industry proven to be quite practical providing always safe results in spite of common uncertainties. The logivcal way is to extend this result for haptic display interaction chains (Fig. 2).

IV. ADMITTANCE DISPLAY CONTROL

Admittance displays measure the forces exerted by the human operator using a force sensor and generate the corresponding displacements. Conventional non-backdrivable and position controlled industrial robots can usually be utilized to realize the interaction based on the admittance model. The principal scheme of the interaction control for an admittance display based on the robust control method developed in the previous sections is sketched in (Fig. 5). The display is presented as a closed loop position system G_p designed to accurately track reference position x_r received from the haptic control system. The reference position is obtained as Δx_F-deviation from an initial position x_0 based on the impedance compensator law [2, 3]

$$G_f(s) = \hat{G}_p(s)^{-1} G_t(s)^{-1} \tag{10}$$

It is relatively easy to prove that this compensator involved in the feedback loop modifies commonly high impedance of the tracking controller G_p, realizing thus compliant desired target impedance behaviour. The input to the haptic compensator (10) is the difference between human and virtual environment forces. In an ideal positional servo $x = x_r$, the computed position is rendered to the operator. The applied impedance controller (10) realizes the target admittance in such a way that the display and the impedance controller can be replaced by Z_t^{-1} (Fig. 5).

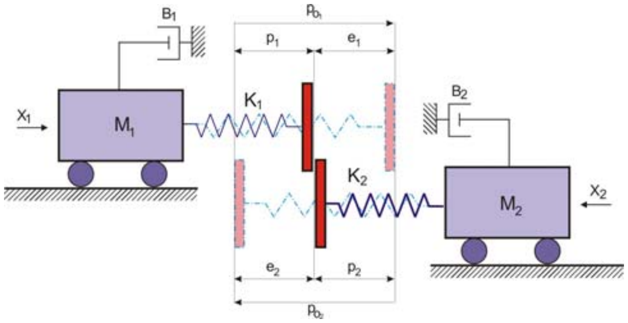

Figure 4. Interaction with an active eenvironment

Hence, interaction between human operator, virtual-coupling (target-impedance) and virtual-environment can be considered based on a simplified model. In a simplified analysis human behavior can be considered as a passive variable impedance [13]. Thus, the contact and coupled stability of admittance displays will be ensured for a robustly stable interaction system presented on (Fig 6). The same stability conditions (8, 9) and corresponding target impedance design algorithms and tools developed for robot/environment interaction [2], can be applied for the design of admittance haptic systems. According to (Fig. 6), the relationship between human and environmental force is defined by

$$F = Z_e(p_0 - e) = Z_e[p_0 - Z_t^{-1}(F - F_h)] \tag{11}$$

providing for a SISO system

$$F = \frac{Z_e}{Z_t + Z_e} F_h + \frac{Z_e Z_t}{Z_t + Z_e} p_0. \tag{12}$$

When considering the above equations and relations, equivalence between the transfer function ($F_h \rightarrow F$), which describes force interaction in an admittance display, and the function ($p_0 \rightarrow e$), which describes robot/environment contact, can be established. Assuming that the operator intends to exert forces upon the virtual wall, the hand force can be, similar to the nominal penetration p_0, considered to have constant direction towards the virtual obstacle during contact establishment.

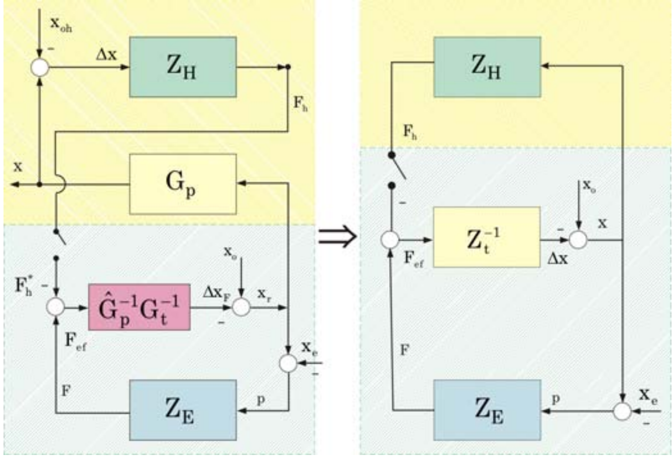

Figure 5. Admittance display control scheme

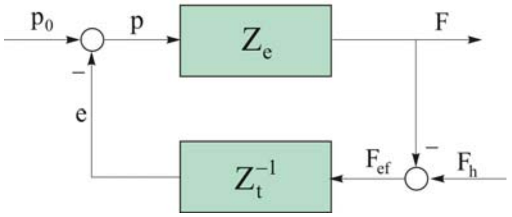

Figure 6. Interaction model

Then, based on *Theorem 2* that defines sufficient condition for robustly stable interaction in the (p_0, e) subsystem, we can write the stability criterion for the considered equivalent (F_h, F) subsystem regarding (12)

$$\left\| Z_e / Z_t + Z_e \right\|_\infty \le 1 \tag{13}$$

which ensures

$$\left\| F \right\|_2 / \left\| F_h \right\|_2 \le 1 \tag{14}$$

This condition defines both stable contact transition and coupled performance. Let us consider the role of p_0 in the model (11) and schemes sketched in (Fig. 5-6). In the haptic system the initial position x_0 (i.e. penetration p_0) is constant and has a different meaning from the nominal position (penetration) in the robot/environment interaction. In effect, in a haptic interface the hand force F_h directs the system motion, while x_0 defines the start location. Conveniently, x_0 is selected in front of the virtual hindrance. Therefore, p_0 ("negative penetration") has no sense in the contact model (11) and can be neglected (p_0=0).

When the complete target impedance is selected $Z_t(s) = M_t s^2 + B_t s + K_t$, and assuming a stiff virtual environment $Z_e = K_e >> K_t$, the interaction system (11) provides the following steady-state performance

$$F^* = \frac{K_e}{K_t + K_e} F_h^* \Rightarrow F^* \approx F_h^* \qquad (15)$$

However, in the free space the applied control (Fig. 6) realizes the target admittance (virtual coupling) $\mathbf{Z_t}^{-1}$ that is rendered to the operator. Since the general admittance exhibits a spring-like behavior, the operator should exert greater force than (15) in order to bring the virtual coupling system into contact with the virtual environment. Consequently the entire steady-state force becomes

$$\begin{aligned} F_h^* &= K_h p^* = K_t \left(x_e - x_0 + p^*\right) + K_e p^* \\ F^* &= K_e p^* \end{aligned} \qquad (16)$$

where p^* denotes equilibrium penetration and K_h is the total stiffness rendered to the operator. From this it is obvious that

$$K_h \geq K_t + K_e \qquad (17)$$

In order to improve transparency, a target-damping virtual coupling (with zero stiffness) can be applied

$$Z_{td}\left(s\right) = M_t s^2 + B_t s \qquad (18)$$

In free space with this virtual coupling the human operator feels only target inertia and damping during motion, while equilibrium hand force becomes zero. In the contact (8), transparency is characterized by

$$F = \frac{K_e}{M_t s^2 + B_t s + K_e} F_h \Rightarrow \quad F^* = F_h^* \qquad (19)$$

The virtual coupling target systems, which can take form of general impedance (2) or damping (18), determines the lower impedance bound of the Z-width achievable with the new control system. Theoretically the maximum bound might be infinite when $K_e \to \infty$.

As demonstrated, by means of the developed robust interaction control design we can synthesize the target systems (virtual couplings) ensuring the contact and coupled stabilities. Practical limitation on the upper Z-width bound governs the control lags, which in haptic systems can be considerably larger in comparison to the robot impedance control. Geometrically and physically complex environments and contact interaction situations might require significant computation efforts to determine forces, causing relatively large delays in a reliable computer control environment. This delay must be considered in the design (Fig. 7). As mentioned above, the new control design provides a unified and efficient framework for continuous as well as SD delayed system synthesis based on the conditions (13-14). In particular this is advantageous for haptic systems. Even more important, by means of weighting functions describing model-uncertainties (6), non-linear environment effects can also be effectively considered in the design.

However, in specific cases the tradeoff of a simplified design could be conservativeness. In other words, the synthesized virtual coupling for a non-linear delayed environment may become quite over-damped causing slow response and sluggish behavior, which significantly reduces the system transparency. This is particularly critical in free-space. In order to overcome this problem, we can apply adaptive virtual coupling with different target systems appropriate for free-space handling, stable transition and interaction with a delayed environment. However, the adaptive compliance control may become very complex and in general it is difficult to implement, requiring a continuous variation of target model parameters in order to avoid oscillations. For relatively simple mass-damper model, continuous variation of the parameters can easily be realized and it was implemented in a handling-manipulator system, to be presented in the next chapter.

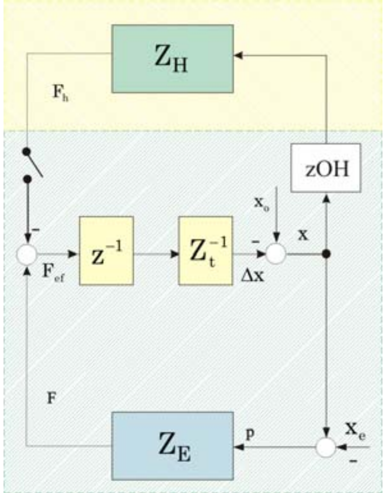

Figure 7. SD addmitance display interaction control

V. EXPERIMENT

The main issue of this experiment is to demonstrate design and performance of the new haptic controller on a simple SISO admittance display (Fig. 8). The experimental system consists of a single linear axis with a direct-drive actuator consisting of a linear hybrid (variable reluctance) stepper motor with air bearings. Similar to DC-motors a *voltage interface* is realized between the internal stepper control and external feedback control. This interface allows closing servo-loops around position sensor (high-resolution linear encoder strip) and forcing sensor (six-DOF SHUNK sensor, see Fig. 8). The position and impedance control (i.e. haptic admittance control) is implemented according to (Fig. 5-7) in SIMULINK and realized using Real Time Workshop (RTW) and real-time dSPACE rapid control prototyping system.

In the experiments the linear drive is located in front of a virtual wall ($K_e = 60000$ N/m). The coupling impedance is selected in the form (18) with the selected target mass $M_t = 10$ (kg). The target damping is computed based on the robust stability condition (8), i.e. based on SD stability criterion (9) taking into account sampling-time T=0.001 (s) and control lag $\tau = 0.001$ (s). Target damping needed to ensure robustly stable interaction is computed using MATLAB and Impedance Control Design Toolbox developed at IPK. For the adopted parameters the required damping amounts $B_t = 1224$ (Ns/m). This relatively higher damping is required to ensure stable transition and interaction with a very stiff environment. Consequently, higher impact velocities with a virtual environment produce considerable forces. Therefore it is practical to select significantly lower damping for free-space motion and to switch to the damping required for contact realization close to the virtual obstacles and realize contact at noticeably lower velocities.

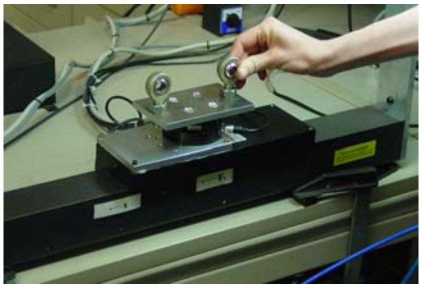

Figure 8. Experimental set-up

The experiments consist in pushing the actuator by hand in the virtual wall direction (Fig. 8) until the contact is achieved, pressing on the wall and pulling back. This procedure was repeated several times. The measured hand force and simulated wall force are presented in (Fig. 9). Obviously, the interaction was stable, and both contact transition stability and coupled stability were reached.

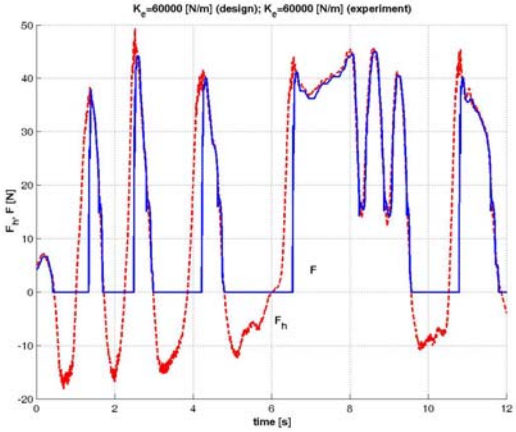

Figure 9. Hand F_h (dashed line) and virtal-wall F (blue-solid line) forces during haptic interaction (Ke=60000 N/m in both design and experiment)

The experiment on (Fig. 10) illustrates the robustness of the applied control design method. In this trial the same coupling impedance synthesized for $K_e = 60000$ is applied for interaction with a significantly stiffer wall $K_e = 100000$ (N/m) without affecting the performance. That means that robust control design approach ensures the interaction stability even when the environment varies twice as assumed in the design. That is the main benefit of the proposed control design upon previous approaches [11, 13].

However, if the stiffness is further increased until $K_e = 150000$, the interaction may becomes instable (Fig. 11). Nevertheless, in case of such drastic parameter variations, after redesign of coupling impedance for the actual environment the contact is again stabilized and similar performance as in initial one in (Fig. 9) has been achieved.

VI. EXTENSION TO 2-DOF HANDLING MANIPULATOR

The developed algorithm was implemented to control a 2-DOF a hand-driven handling-manipulator (x-y railway crane) with 100kg payload capacity (Fig. 12). Each DOF is actuated by a friction drive actuator in order to achieve power-assistance. The position of the hub is measured using laser distance sensors. Chip x-y force sensors were integrated in the hand grippers to measure hand control forces.

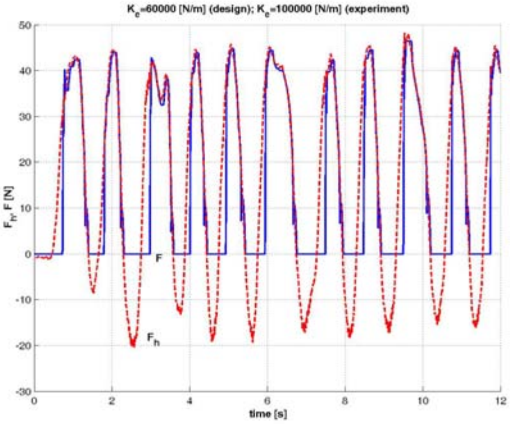

Figure 10. Robustness of interaction control design (Ke=60000 N/m design; Ke=100000 N/m experiment)

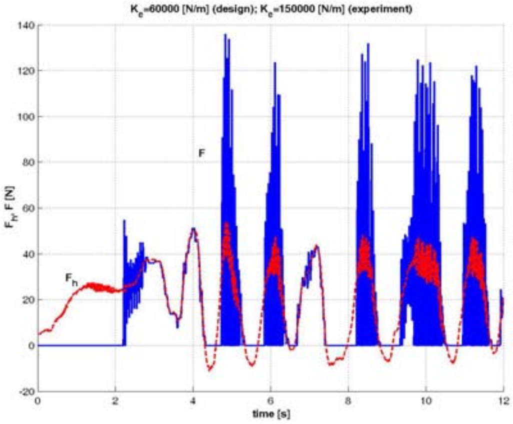

Figure 11. Unstable innteraction (Ke=60000 N/m design; Ke=150000 N/m experiment)

Although referred to as "KOBOT" (i.e. Cobot – collaborative robot) this system (representing first "cobotic" device at European market) indeed represents an admittance display. The developed algorithms were applied to display to operator different admittances as well as virtual obstacles (walls) introduced in the working space in order to constraint the motion or to guide (slide) the hub to a target position. In order to manipulate heavy payloads ergonomically with minimum strain exerted upon operator a hand force amplification is introduced. Taking into account relatively high perturbations of force and position measurements, the admittance control was implemented in the open loop. To synthesize target impedances ensuring stable interaction with a stiff environment (K_e=5000 N/m) the stability condition (8) was applied providing a mass-damper coupled impedance $Z_t(s) = 10s^2 + 140s$ which ensure robust stability of interaction with a virtual wall.

Encouraging initial experiments (Fig. 13) with polygonal virtual walls, modelled as pure stiffness environment, have clearly demonstrated the robust contact stability, even in open loop control (in spite of sensing and control perturbations). This demonstrates practical applicability of novel haptic stability criterion. A stable interaction without bouncing is very important for this application in order to achieve an efficient and ergonomics smooth guidance of high-inertia payloads along virtual walls.

VII. CONCLUSION

Robust contact stability theory initially developed for controlling robot/environment interaction, has been expanded to control and synthesis of haptic interfaces interacting with a virtual environment. This rapidly emerging technology imposes high requirements on interaction stability and robustness of control system. New control approaches for admittance displays control based on impedance control and contact stability results were for the first time proposed in this paper. Simple experiments results have demonstrated advantages, high performance and reliability of the new algorithms in both open and closed control applications.

The advantageous of robust stability was especially demonstrated in interaction control of an intelligent power-assisted railway crane with significant perturbations on force and position measurements. Further implementation in more complex haptic interfaces, as well in other advanced interactive systems, such as human enhancer and rehabilitation robots, are actually under development.

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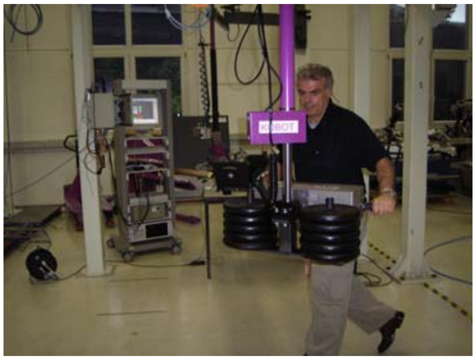

Figure 12. Railway crane admittance display with 100 kg payload

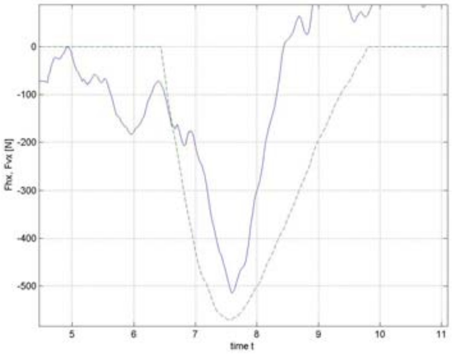

Figure 13. Amplified hand force(solid line) and virtual interaction force (dashed line) during contact with a virtual wall (for ergonomics reasons, hand force is scaled by a factor of 10)

Acknowledgment This research was partially supported by EU IP-Project PISA (Flexible Assembly Systems Through Workplace-Sharing and Time-Sharing Human-machine Cooperation) focused on human-centered assembly concepts and technology (Proj. Nr. 026697-2).