Robust Stability Analysis of a Bilateral Teleoperation System Using the Parameter Space Approach

Angelika Peer and Martin Buss

***Abstract*— One of the main challenges in telerobotics is the selection of control architectures and control parameters, which are able to robustly stabilize the overall teleoperation system despite of changing human operator and environment impedances. In this paper robust stability of different types of bilateral control algorithms for admittance-type devices is analyzed. Hereby stability of the system is investigated by using the parameter space approach, which allows the analysis of uncertain systems with varying plant parameters. Stability of the teleoperation system is analyzed by using linear models for human-system interface and teleoperator. The parameter space approach is adopted for controller design as well as for robustness analysis. Robust stability of the presented control architectures is evaluated for a real mechatronic teleoperation system.**

I. Introduction

In a teleoperation system a human operator controls a remotely located teleoperator by a human-system interface. Fig. 1 shows a typical bilateral teleoperation system formed by the main components human operator, human-system interface, communication channel, teleoperator, and environment. Hereby master and slave devices are controlled by local controllers, which are coupled with each other over the communication channel. Since the human operator can behave in vary different ways and interact with different kind of remote environments ranging from free space to hard contact, one of the main challenges in telerobotics is the selection of robustly stable control architectures and corresponding control parameters. Typical approaches are either based on the passivity theorem [1], see e.g. [2]–[4], or the analysis of absolute stability by using Llewellyns stability criteria [5], see [6], [7] for examples. But the drawback of these approaches is that a passive human operator and remote environment have to be assumed and no desired dynamics of the teleoperation system can be commanded. This work aims for analyzing stability by using the so-called parameter space approach [8], which allows the analysis of uncertain systems with varying plant parameters without assuming passive behavior. It is shown how this method can be applied for controller design as well as for robustness analysis of a bilateral teleoperation system. Although the specific numerical results are only valid for the analyzed teleoperation system, the form of the stability regions is generalizable and holds also for other admittance-type teleoperation systems controlled by the same proposed control architectures. Thus the main contribution of this work is twofold: firstly it is shown how the parameter-space approach can be applied to bilateral teleoperation systems for controller design and robustness analysis, and secondly different types of control architectures for admittance-type devices are analyzed, robustly stabilizing control parameter regions are identified and rules for the selection of them are formulated.

Fig. 1. Bilateral teleoperation system

In the following section different types of bilateral control architectures for admittance-type devices are presented. Sec. III shows the principle of the parameter space approach and Sec. IV introduces the models used for stability analysis. Finally in Sec. V robust stability of the presented control architectures is analyzed for a real mechatronic teleoperation system.

II. Bilateral control architectures for admittance-type devices

Control architectures for bilateral teleoperation systems are commonly classified according to the number and kind of variables transmitted between master and slave device, see [9] for an overview. So called two-channel control architectures, whereby master and slave are connected with each other via two communication channels, represent possibly the most popular bilateral controllers, see [10] for details. Hereby, forces/positions are exchanged between master and slave device and local position or force controllers are used. While for impedance-type devices, which are characterized by very light-weight constructions with low inertia and friction, high performance force controllers can be implemented, for admittance-type devices, force control can only be realized with a very poor performance [11]. This is mainly due to the high dynamic properties and friction effects of admittance-type devices, which can only be compensated by using some kind of low level position controller. On this account, classical bilateral control architectures with local force control are usually not very appropriate for teleoperation systems using admittance-type master and slave devices.

Commonly, admittance-type devices are controlled by using a so called position-based admittance control architecture, see [11]. The hereby implemented low-level position controller compensates for the before mentioned non-linear

A. Peer, and M. Buss are with the Institute of Automatic Control Engineering, Technische Universität München, Germany. Angelika.Peer@tum.de, mb@tum.de

effects. Depending on the application, such an architecture can be used either to render a target dynamics as e.g. the mass of a tool or to achieve a certain compliant behavior when being in contact with the environment. In both cases the desired behavior is achieved by implementing impedances in form of simple mass-spring-damper systems.

In view of the classical two-channel control architectures, position-based admittance controllers can be implemented for master, as well as slave devices and combined into a teleoperation control architecture when positions and forces are exchanged. The selection of appropriate impedance parameters decides hereby on stability and transparency of the overall teleoperation system. Observe e.g. that ideal transparency cannot any more be achieved due to the implemented desired master and slave impedances.

In principle three different basic bilateral control architectures using admittance-type controllers can be realized:

A. Position-based admittance control with position-force exchange (FaPa)

In the position-based admittance control with position-force exchange, which is slightly adapted from the control architecture introduced in [12], positions are sent from master to slave and forces from slave to master, see Fig. 2. Admittance-type controllers are used to control master as well as slave device. The corresponding control laws are given by

$$f_m = D_{xm}\left(\dot{x}_{dm} - \dot{x}_m\right) + K_{xm}\left(x_{dm} - x_m\right), \tag{1}$$

$$f_s = D_{xs}\left(\dot{x}_m - \dot{x}_{ds} - \dot{x}_s\right) + K_{xs}\left(x_m - x_{ds} - x_s\right), \tag{2}$$

$$f_{ss} - f_{sm} = m_{dm}\ddot{x}_{dm} + b_{dm}\dot{x}_{dm}, \tag{3}$$

$$f_{ss} = m_{ds}\ddot{x}_{ds} + b_{ds}\dot{x}_{ds} + c_{ds}x_{ds} \tag{4}$$

for master and slave. While at master side a sort of force control is implemented, at slave side a compliant controller is realized. During free space motion only the master impedance given by m_{dm} and b_{dm} is active, the slave side is controlled by a pure position controller. In contact also the slave impedance is active and both controllers influence the impression of the remote environment. It should particularly be noted that the stiffness parameter c_{ds} defines an upper bound of displayable stiffnesses.

B. Position-based admittance control with force-position exchange (PaFa)

The position-based admittance control with force-position exchange represents the mirrored version of the last presented control architecture: forces are sent from master to slave and positions from slave to master. The corresponding control laws are given by

$$f_m = D_{xm}\left(\dot{x}_s - \dot{x}_{dm} - \dot{x}_m\right) + K_{xm}\left(x_s - x_{dm} - x_m\right), \tag{5}$$

$$f_s = D_{xs}\left(\dot{x}_{ds} - \dot{x}_s\right) + K_{xs}\left(x_{ds} - x_s\right), \tag{6}$$

$$-f_{sm} = m_{dm}\ddot{x}_{dm} + b_{dm}\dot{x}_{dm} + c_{dm}x_{dm}, \tag{7}$$

$$f_{ss} - f_{sm} = m_{ds}\ddot{x}_{ds} + b_{ds}\dot{x}_{ds}. \tag{8}$$

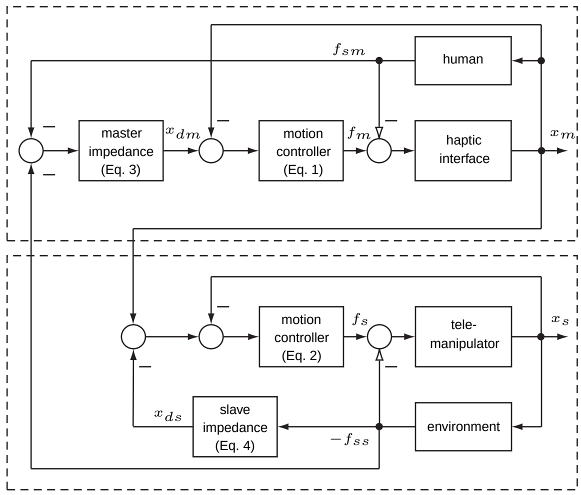

Fig. 2. Position-based admittance control with position-force exchange (FaPa)

C. Position-based admittance control with force-force exchange (FaFa)

Finally, the position-based admittance control with force-force exchange is characterized by a bilateral force-force exchange between master and slave. At both sides an admittance control strategy is implemented:

$$f_m = D_{xm}\left(\dot{x}_{dm} - \dot{x}_m\right) + K_{xm}\left(x_{dm} - x_m\right), \tag{9}$$

$$f_s = D_{xs}\left(\dot{x}_{ds} - \dot{x}_s\right) + K_{xs}\left(x_{ds} - x_s\right), \tag{10}$$

$$f_{ss} - f_{sm} = m_d\ddot{x}_{dm} + b_d\dot{x}_{dm}, \tag{11}$$

$$f_{ss} - f_{sm} = m_d\ddot{x}_{ds} + b_d\dot{x}_{ds}. \tag{12}$$

In order to guarantee position tracking the same impedances given by the mass m_d and the damping b_d have to be implemented for master and slave. On this account, only two control parameters have to be selected, which simplifies tuning of the controller significantly.

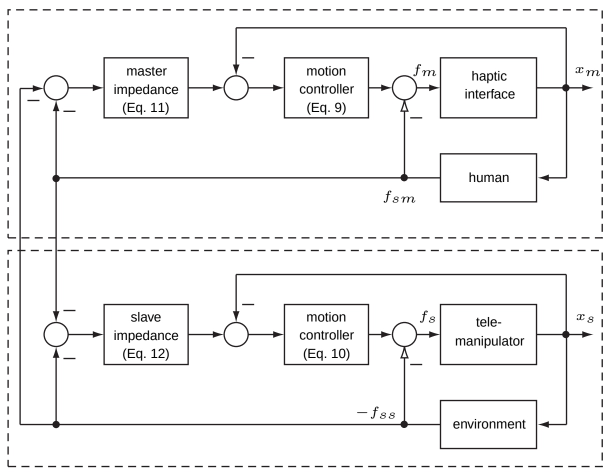

Fig. 3. Position-based admittance control with force-force exchange (FaFa)

III. PARAMETER SPACE APPROACH

Since in telemanipulation systems the operator interacts with environments of different impedances, we have to deal with an uncertain plant defined by the operating domain Q:

$$Q = \left\{ \boldsymbol{q} \mid q_i \in \left[q_i^-, q_i^+ \right], i = 1, 2, ..., l \right\}. \tag{13}$$

In this work the stability analysis is performed by applying the parameter space approach [8], which allows the analysis of uncertain systems with varying plant parameters. It is based on the boundary crossing theorem of polynomials stated by Frazer and Duncan [13]. Given the linear state space model

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}, \quad (14) \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u}, \quad (15) \end{aligned}$$

and the corresponding characteristic polynomial

$$p(s, \boldsymbol{q}) = \det(s\boldsymbol{E} - \boldsymbol{A}) = 0, \tag{16}$$

stability can be analyzed as follows:

The parameter space approach allows mapping of stability regions (in the following referred as Γ-region) defined in the s-plane

$$\delta\Gamma := \left\{ s \mid s = \sigma(\lambda) + j\omega(\lambda), \lambda \in \left[\lambda^-, \lambda^+ \right] \right\} \tag{17}$$

into the parameter space formed by l uncertain plant or control parameters collected in the parameter vector $\boldsymbol{q}$. Hereby λ means a generalized frequency. According to the boundary crossing theorem, starting from a stable characteristic polynomial $p(s, \boldsymbol{q})$, a polynomial with real coefficients $a_i(\boldsymbol{q})$ can only become unstable if the system crosses the stability boundary. Depending on whether the stability boundary is crossed on the real axis, imaginary axis or at infinity, real root boundaries (RRB), complex root boundaries (CRB) and infinite root boundaries (IRB) are distinguished. These boundaries are mapped into the parameter space by solving the following equations for the uncertain parameters $q_i = f(\lambda)$:

$$\begin{array}{ll} \text{RRB:} & p(\sigma_0, \boldsymbol{q}) = 0 \quad \text{with } \sigma_0 \text{ the} \\ & \text{intersection point of the real axis with } \delta\Gamma, \\ \text{IRB:} & \lim\limits_{\lambda \to \infty} p(\sigma(\lambda) + j\omega(\lambda), \boldsymbol{q}) = 0, \\ \text{CRB:} & \Gamma_{CRB} := \{ \boldsymbol{q} \mid p(\sigma(\lambda) + j\omega(\lambda), \boldsymbol{q}) = 0, \\ & p(\sigma + j\omega) \in \delta\Gamma, \lambda \in \left[\lambda^-, \lambda^+ \right] \} \end{array} \tag{18}$$

The parameter space method can be either used for controller design or for robustness analysis, depending on whether the stability region is mapped into the parameter space of control parameters or varying plant parameters.

a) Controller design: The stability boundaries are mapped into a plane formed by two control parameters k_1, k_2. This allows to determine the set of control parameters for which the system is Γ-stable. If a system with n control parameters is considered, $n-2$ control parameters must be fixed to a certain value, while the rest can be gridded. For each grid point the Γ-stability boundaries are computed and projected into the selected parameter plane.

Designing a controller for an uncertain plant requires basically two steps: In a first step sets of stabilizing controllers for some representative operating points (typically the vertices of the operating domain) have to be computed. The intersection of all these sets guarantees Γ-stability for all representative operating points, but not necessarily for the whole operating domain. After selection of appropriate control parameters this has to be verified in a second step by a robustness analysis.

b) Robustness analysis: The stability boundaries are mapped into a plane formed by two varying plant parameters q_1, q_2. The system is robustly Γ-stable if the entire operating domain is contained in the Γ-stable parameter set.

IV. MODELLING OF THE TELEOPERATION SYSTEM

To analyze stability of the teleoperation system a state space model of the overall system including haptic interface, telemanipulator, human and environment is needed. In the context of this work simple one degree of freedom models for haptic interface and telemanipulator are used. The human operator and the environment are modelled by using linear mass-spring-damper models. In the following these models are described in more detail.

A. Haptic interface and human operator

A very simple way to model a haptic interface is to use a mass-damper system [3] as shown in Fig. 4. Hereby m_m means the haptic interface mass and b_m the damping coefficient. The actuator force is modelled by f_m.

Since the human operator interacts with the haptic interface also a simple model of the human arm is needed. According to [14] a simple mass-spring-damper model can be used. In this context m_h means the human arm mass, c_h the human arm stiffness and b_h the human arm damping. The factor $\alpha \in [0, 1]$ is used to take into account variable human arm impedances. The exogeneous force applied by the human operator is modelled by f_h. Finally m_{em} means the end-effector mass and f_{sm} the force measured by the force-torque sensor located at the tip of the haptic interface.

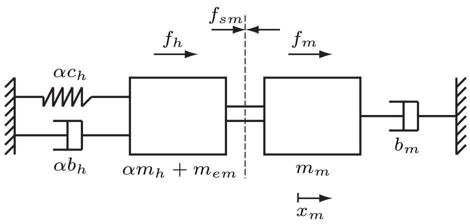

Fig. 4. Model of human system interface and human operator

The overall system described in Fig. 4 is represented by the following differential equations:

$$\begin{aligned} 0 &= f_h + f_{sm} - (\alpha m_h + m_{em})\ddot{x}_m, \quad (19) \\ &\quad -\alpha b_h \dot{x}_m - \alpha c_h x_m, \\ 0 &= f_{sm} - f_m + m_m \ddot{x}_m + b_m \dot{x}_m. \end{aligned}$$

B. Telemanipulator and environment

The telemanipulator is modelled analogously, whereby m_s means the telemanipulator mass, b_s the telemanipulator damping, and f_s the force applied by the actuators. The environment the telemanipulator interacts with is modelled by a mass-spring-damper model. The end-effector mass and load is modelled by m_{es}, k_e and b_e mean the environmental stiffness and damping coefficient. The overall system is shown in Fig. 5 and can be described by using the following differential equations:

$$\begin{aligned} 0 &= f_s + f_{ss} - m_s\ddot{x}_s - b_s\dot{x}_s, \\ 0 &= f_{ss} + m_{es}\ddot{x}_s + b_e\dot{x}_s + c_e x_s. \end{aligned} \tag{20}$$

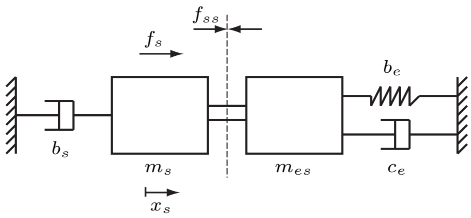

Fig. 5. Model of telemanipulator and environment

C. Actuator and sensor dynamics

In order to reproduce effects visible in the real hardware experiment also non-ideal actuator dynamics must be considered. On this account the electrical motor time constant T_a is modelled by a low pass filter.

V. Stability Analysis

In this section stability of the above presented control algorithms for bilateral teleoperation is analyzed by using the parameter space approach. Hereby in a first step sets of control parameters which stabilize the overall teleoperation system are determined and then a robustness analysis is carried out for one special set of control parameters.

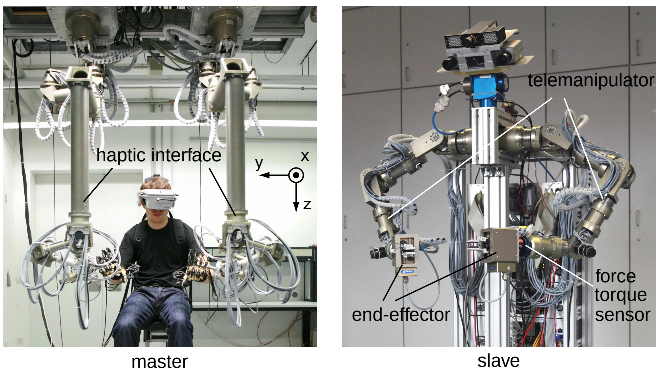

Fig. 6. Teleoperation system consisting of a redundant haptic interface [15] and a redundant telemanipulator [16]

The numerical stability analysis is carried out for a teleoperation system consisting of a redundant haptic interface [15] as well as a redundant telemanipulator [16], see Fig. 6. Both manipulators are built using commercially available components combined with aluminum/steel construction elements. The actuation torque is provided by dc motors coupled with harmonic drive gears.

In order to simplify the analysis for this multi d.o.f. system a dynamic compensation of the cross-couplings between the linkages is assumed, such that each degree of freedom can be evaluated separately. Moreover, in order to reduce the number of control parameters, the low level position controllers are assumed to be already tuned. They are selected in such a way that aperiodic transient responses are achieved. The stability analysis is performed by adopting the models presented above. The model parameters used for simulation are reported in Table I. They refer to motions in x and y direction as indicated in Fig. 6.

TABLE I
Simulation parameters of rigid model

parameter	value
m_m	23 kg
b_m	20 Ns/m
m_{em}	0.334 kg
m_s	13.5 kg
b_s	20 Ns/m
m_{es}	1.9 kg
T_a	0.0003 s
K_{xm}	5750000
D_{xm}	23000
K_{xs}	5750000
D_{xs}	13500

All simulations were carried out for a three-dimensional operating domain formed by the varying parameters: environment stiffness $c_e \in [0 \quad 10,000]$ N/m, environment damping $b_e \in [0 \quad 200]$ Ns/m, and load mass $m_{ee} \in [m_{es}^{min} \quad m_{es}^{min}+1]$ kg, see Fig. 7. This assumption is made because in a teleoperation system the operator can interact with different kind of environments, ranging from free space to hard contact. In addition the operator can grasp objects, which has to be considered in the model. On this account a varying load mass m_{es} is introduced, whereby the lower bound is given by the end-effector mass only.

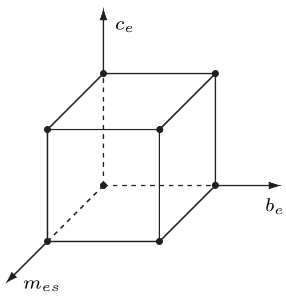

Fig. 7. Operating domain formed by environment stiffness, environment damping, and end-effector mass (including load mass)

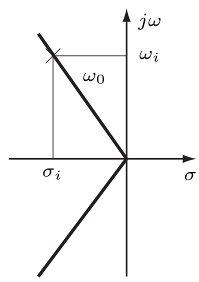

Fig. 8. Γ-region with damping $d = -\sigma_i/\omega_0$

In the following results of the numerical stability analysis for the above presented bilateral teleoperation control schemes are reported.

1) Position based admittance control with position-force exchange (FaPa): Using the position-based admittance control with position-force exchange five control parameters m_{dm}, b_{dm}, m_{ds}, b_{ds}, and c_{ds} have to be selected to guarantee stability of the overall teleoperation system. Hereby m_{dm}, b_{dm} mostly affect the free space behavior and m_{ds}, b_{ds}, c_{ds} the impression of contact. Further it is known that due to the admittance-type control the minimum target inertia of the master device is bounded by stability. On this account, m_{dm} has been set to a value which stabilizes the haptic interface, when used in standalone mode. In order to further reduce the number of control parameters $c_{ds} = 600$ N/m has been fixed. It should be noted that the stiffness parameter c_{ds} mainly influences the perception of stiff environments since it introduces an upper bound for displayable stiffnesses. Thus, it should be selected carefully.

In the first step Hurwitz stability is analyzed. Fig. 9 shows the resulting stability boundaries that are mapped into the m_{ds}, b_{ds} plane for two different values of α. As can be seen lowering the human arm impedance reduces the set of stabilizing controllers. Each of the lines represent a set of stability margins determined for one of the eight vertices of the operating domain defined in Fig. 7. The intersection of all these sets describes control parameters which stabilize all representative operating points. In order to distinguish stable and non-stable regions it is enough to check stability of an arbitrary point per region. If the point is stable, then, according to the boundary crossing theorem of polynomials, all control parameters in this region stabilize all representative operating points. Out of these robustly stabilizing controllers one can be selected, whereby the choice depends strongly on further performance criteria, as e.g. transparency. When selecting a controller, impedances should be chosen, that only slightly affect the impression of the remote environment as well as the transparency of the overall teleoperation system.

To check if the selected controller (*) not only stabilizes the representative operating points, but also the whole operating domain, a robustness analysis must be performed, see Fig. 10. As can be seen, the selected controller allows to robustly Γ-stabilize the teleoperation system since the entire operating domain is enclosed by the Γ-stability margins. Hereby each line stays for lower and upper bound of the end-effector mass m_{es}.

After implementing this control algorithm in the real hardware setup a relatively low damped behavior could be observed, when touching stiff environments. On this account, the analysis presented before has been carried out again for a new Γ-region as shown in Fig. 8. This new Γ-region guarantees a certain damping $d = -\sigma_i/\omega_0$ of the overall system. Fig. 11 shows the result of the corresponding stability analysis. Although a relatively small damping coefficient has been selected, the set of stabilizing controllers is reduced significantly. Increasing the damping coefficient even further would cause a dramatical reduction of stabilizing controller sets. This again indicates that a certain amount of slave damping and a low slave mass have to be implemented

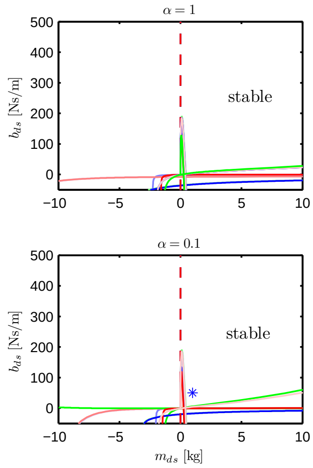

Fig. 9. FaPa architecture: Stability boundaries of the vertices of the operating domain in the (m_{ds}, b_{ds})-plane depending on the human arm impedance α ($m_{dm} = 6$ kg, $b_{dm} = 0$ Nm/s, $c_{ds} = 600$ N/m).

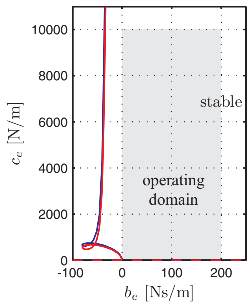

Fig. 10. Robustness analysis for FaPa-architecture: Stability boundaries of the vertices of the operating domain in the (b_e, c_e)-plane for $\alpha = 0.1$ ($m_{dm} = 6$ kg, $b_{dm} = 0$ Ns/m, $m_{ds} = 1$ kg, $b_{ds} = 50$ Ns/m, $c_{ds} = 600$ N/m).

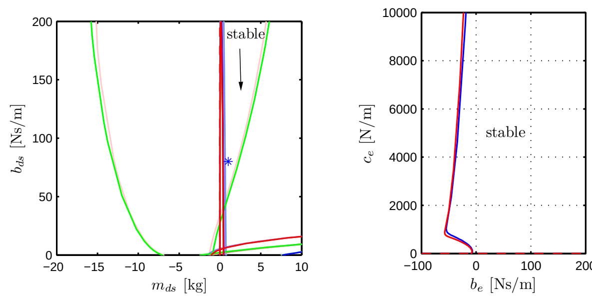

Fig. 11. FaPa architecture: Stability boundaries of the vertices of the operating domain in the (m_{ds}, b_{ds})-plane and robustness analysis in the (b_e, c_e)-plane for a damping of $d = -0.1$ ($\alpha = 0.1$, $m_{dm} = 6$ kg, $b_{dm} = 20$ Nm/s, $m_{ds} = 1$ kg, $b_{ds} = 80$ Ns/m, $c_{ds} = 600$ N/m).

in order to guarantee a good damped behavior, otherwise the interaction with stiff environments would inevitably cause oscillations. Hereby it should be noted that due to actuator limitations there are also lower bounds on the slave and master mass m_{ds} and m_{dm} that can be implemented without causing instability of the teleoperator. A further very interesting result is that the damping parameter b_{dm} is not only lower, but also upper bounded, which indicates that introducing more damping into the teleoperation system does not always help to stabilize it.

2) Position based admittance control with force-position exchange (PaFa): Again five control parameters m_{dm}, b_{dm}, c_{dm}, m_{ds}, b_{ds} have to be selected in order to guarantee Γ-stabilizing behavior. The same principle as presented above is used to reduce the number of variable control parameters: m_{ds} is selected to stabilize the telemanipulator alone and c_{dm} is set to a fix value.

Fig. 12 shows the result of the parameter space approach, whereby the stability margins dependent on the human arm

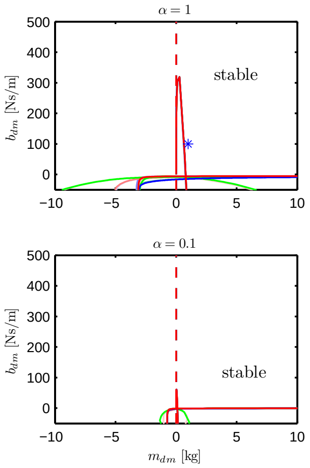

Fig. 12. PaFa architecture: Stability boundaries of the vertices of the operating domain in the (m_{dm}, b_{dm})-plane depending on the human arm impedance α ($m_{ds} = 6$ kg, $b_{ds} = 20$ Ns/m, $c_{dm} = 600$ N/m).

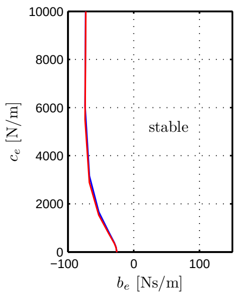

Fig. 13. Robustness analysis for PaFa-architecture: Stability boundaries of the vertices of the operating domain in the (b_e, c_e)-plane for $\alpha = 1$ ($m_{dm} = 1$ kg, $b_{dm} = 100$ Ns/m, $c_{dm} = 600$ N/m, $m_{ds} = 6$ kg, $b_{ds} = 2($

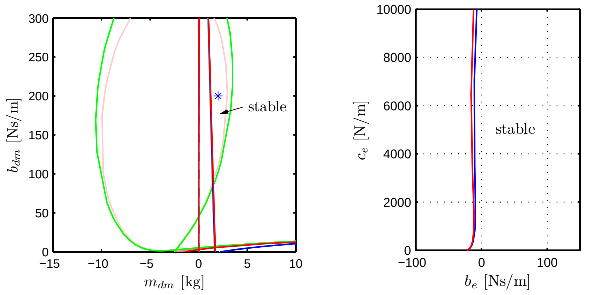

Fig. 14. PaFa architecture: Stability boundaries of the vertices of the operating domain in the (m_{dm}, b_{dm})-plane and robustness analysis in the (b_e, c_e)-plane for a damping of $d = -0.1$ ($\alpha = 1$, $m_{dm} = 2$ kg, $b_{dm} = 200$ Nm/s, $c_{dm} = 600$ N/m, $m_{ds} = 6$ kg, $b_{ds} = 20$ Nm/s).

impedance are drawn. In contrast to the before presented architecture smaller human operator impedances have a stabilizing effect on the system. The corresponding robustness analysis is shown in Fig. 13.

Finally again a Γ-region with damping $d = -0.1$ is selected to determine the influence on the control parameters, see Fig. 14. To robustly stabilize the overall teleoperation system a relatively high master damping and low master mass have to be implemented. In contrast to the architecture presented before the unstable region close to zero, which is mainly due to the actuator limitation, is more developed, but again upper and lower bounds on the master mass and damping coefficients exist.

3) Position based admittance control with force-force exchange (FaFa): Using a position-based admittance control with force-force exchange, position tracking can only be guaranteed if equal desired impedances are selected at master as well as slave side. Thus, the number of control parameters can be reduced to a minimum of two variable parameters m_d, b_d.

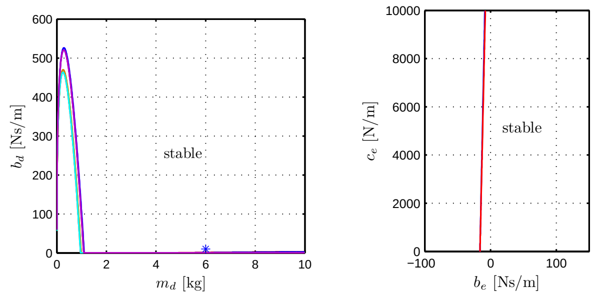

Fig. 15. FaFa architecture: Stability boundaries of the vertices of the operating domain in the (m_d, b_d)-plane and robustness analysis in the (b_e, c_e)-plane ($\alpha = 1$, $m_d = 6$ kg, $b_d = 10$ Ns/m).

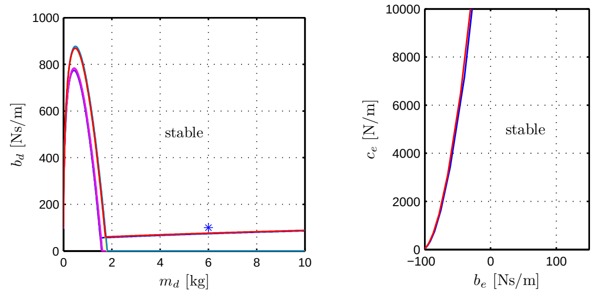

Fig. 16. FaFa architecture: Stability boundaries of the vertices of the operating domain in the (m_d, b_d)-plane and robustness analysis in the (b_e, c_e)-plane a damping of $d = -0.1$ ($\alpha = 1$, $m_d = 6$ kg, $b_d = 100$ Ns/m).

The results of the stability analysis is shown in Fig. 15. It can be observed that a single mass is enough to stabilize the overall system, a small damping, however, enhances stability. Hereby, m_d should be selected at least so large that haptic interface and telemanipulator are stable when they are operated alone. Fig. 15 right shows the stability boundaries in the b_e, c_e-plane. It can be seen that the selected control parameters stabilize the overall operating domain. Finally, selecting a Γ-region with damping $d = -0.1$ a certain amount of damping is necessary to Γ-stabilize the system when being in contact with stiff remote environments, see Fig. 16.

VI. Summary and Conclusion

A stability analysis for different types of bilateral teleoperation control architectures has been carried out. While most existing publications in this field focus on control algorithms for impedance-type devices, this work analyzed different bilateral control architectures for teleoperation systems using admittance-type devices. Robust stability of them has been investigated by using the parameter space approach, which allows the analysis of uncertain systems with varying plant parameters. The main advantage of this method is that in contrast to other approaches known in the literature, no passive human operator, as well as remote environment have to be assumed and a desired dynamics of the overall teleoperation system can be guaranteed. Simple impedance models with varying parameters have been used and effects as actuator dynamics has been considered by simply incorporating them in the dynamical equations.

The performed stability analysis showed that for all considered control architectures robustly stabilizing control parameters can be found, which, however, lead to more or less transparent teleoperation systems. Although the obtained specific numerical results are only valid for the analyzed teleoperation system, the form of the stability regions is generalizable and holds also for other admittance-type teleoperation systems controlled by the same proposed control architectures. In detail the stability analysis led to the following results:

To achieve a damped behavior using a *position-based admittance control with position-force exchange (FaPa)* the slave mass and damping coefficient must be located into a certain interval, because Γ-stability imposes lower and upper bounds on these two parameters. Hereby relatively low slave masses must be selected. In doing so, however, also a lower bound on these masses due to actuator and sensor limitations has to be taken into account. Finally, an increasing human arm impedance has been found to increase the set of stabilizing controllers.

For the *position-based admittance control with force-position exchange (PaFa)* architecture in principle similar stability regions as for the position-based admittance control with position-force exchange can be observed. Stable controller sets are characterized by a small master mass m_{dm} and a certain amount of master damping b_{dm}, whereby again upper bounds for both parameters have to be taken into account. In contrast to the FaPa architecture, increasing human operator impedances decrease the set of stabilizing controllers.

Finally, the *position-based admittance control with force-force exchange (FaFa)* has the lowest number of control parameters and thus is very easy to tune. Depending on the mass distribution in the teleoperation system, the overall system can be stabilized by implementing either a desired mass only or a certain combination of mass and damping coefficient. Increasing the damping coefficient allows to achieve a well damped behavior.

Summarizing, it can be stated that for all analyzed architectures stabilizing controller sets have been found. The *position-based admittance control with position-force exchange* achieves hereby the best transparency as only low impedance parameters are necessary at operator side. The *position-based admittance control with force-force exchange*, however, is much easier to tune, because of the limited number of control parameters. For a multi-d.o.f. system this is of special importance, as the number of parameters increases with each motion possibility and already selected parameters for one degree of motion can influence the others.

ACKNOWLEDGMENTS

This work is supported in part by the German Research Foundation (DFG) within the collaborative research center SFB453 "High-Fidelity Telepresence and Teleaction".

REFERENCES

[1] G. Raisbeck, "A Definition of Passive Linear Networks in Terms of Time and Energy," *Journal of Applied Physics*, vol. 25, pp. 1510–1514, 1954.

[2] D. Lawrence, "Stability and Transparency in Bilateral Teleoperation," *IEEE Trans. on Robotics and Automation*, vol. 9, no. 5, pp. 624–637, 1993.

[3] Y. Yokokohji and T. Yoshikawa, "Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling-Formulation and Experiment," *IEEE Trans. on Robotics and Automation*, vol. 10, no. 5, pp. 605 – 620, 1994.

[4] D. Lee and M. Spong, "Passive Bilateral Teleoperation With Constant Time Delay," *IEEE Trans. on Robotics and Automation*, vol. 22, no. 2, pp. 269–281, 2006.

[5] F. B. Llewellyn, "Some Fundamental Properties of Transmission Systems," in *Proc. of the IRE*, vol. 40, March 1952, pp. 271–283.

[6] R. J. Adams and B. Hannaford, "Stable Haptic Interaction with Virtual Environments," *IEEE Trans. on Robotics and Automation*, vol. 14, no. 3, pp. 465–474, 1999.

[7] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of Control Architectures for Teleoperation Systems with Impedance/Admittance Master and Slave Devices," *The International Journal of Robotics Research*, vol. 20, no. 6, pp. 419–445, June 2001.

[8] J. Ackermann, *Robust Control, The Parameter Space Approach*, 2nd ed. London: Springer, 2002.

[9] S. Hirche, M. Ferre, J. Barrio, C. Melchiorri, and M. Buss, "Bilateral Control Architectures for Telerobotics," in *Advances in Telerobotics*, M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, Eds. Berlin: Springer STAR series, 2007.

[10] J. Kim, P. Chang, and H. Park, "Transparent Teleoperation Using Two-Channel Control Architectures," in *Proc. of the IEEE/RSJ International Conference on Robots and Systems*, 2005, pp. 2824–2831.

[11] M. Ueberle and M. Buss, "Control of Kinesthetic Haptic Interfaces," in *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop on Touch and Haptics*, 2004.

[12] H. C. Cho and J. H. Park, "Impedance Controller Design of Internet-Based Teleoperation Using Absolute Stability Concept," in *IEEE/RSJ International Conf. on Intelligent Robots and Systems*, October 2002, pp. 2256–2261.

[13] R. Frazer and W. Duncan, "On the Criteria for the Stability of Small Motions," in *Proc. of the Royal Society, Series A*, vol. 124, 1929, pp. 642–654.

[14] D. Lawrence and J. Chapel, "Performance Trade-Offs for Hand Controller Design," in *Proc. of the IEEE International Conference on Robotics and Automation*, 1994, pp. 3211–3216.

[15] M. Ueberle, N. Mock, and M. Buss, "Design, Control, and Evaluation of a Hyper-Redundant Haptic Interface," in *Advances in Telerobotics: Human System Interfaces, Control, and Applications*, M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, Eds. Springer, STAR series, 2007.

[16] B. Stanczyk and M. Buss, "Development of a Telerobotic System for Exploration of Hazardous Environments," in *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sendai, Japan, 2004, pp. 2532–2537.