

A Coordinating Controller for Improved Task Performance in Multi-User Teleoperation

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Abstract A teleoperation system extends cognitive and manipulatory skills of a human to a remote site. Here, a multi-user teleoperation system consisting of two haptic interfaces and two teleoperator arms is considered. In addition to a position-based admittance control scheme between corresponding master and slave systems, we introduce a virtual coupling as coordinating controller between the two master and slave systems. Using a robust stability analysis we determine enlarged stability regions in the parameter space compared to the case without coordinating controller. As shown in a complementary paper, an evaluation of the proposed approach moreover yields significant improvements in performance and efficiency.

Keywords: teleoperation, telepresence, collaboration, multi-user, coordinating controller, robust stability, stability analysis, parameter-space approach

1 Introduction

Teleoperation has been a topic of ongoing research for many years. Hereby, haptic interaction over teleoperation systems is especially interesting and challenging due to the bilateral energy exchange involved in the process. Please refer to [1] for an overview of research conducted in this field.

So far, however, only little work considered multi-user teleoperation systems like the one illustrated in Fig. 1. An extension of controllers developed for autonomous multi-robot systems ([2,3,4]) to teleoperation was pursued in

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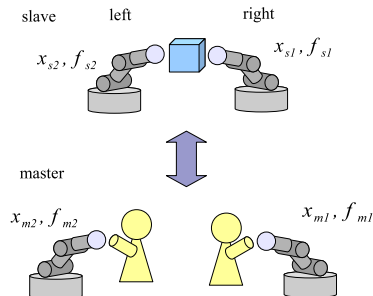


Figure 1: Schematics of the multi-user teleoperation system considered in this work.

[5]. Hereby, interaction with an object is controlled using an internal force controller. The object dynamics of the environment is canceled and replaced by that of a virtual object using an adaptive-control approach [6]. Thus, dynamic properties of the environment are not observable by the operators, and forces applied to the object are predefined by the desired internal force. In teleoperation this is undesirable, as object properties should be transparently perceivable by the operators, and forces applied to the environment must be directly controllable, e.g. in cases where sensitive objects are manipulated.

In previous work, a multi-modal multi-user teleoperation system has been developed [7] and a complex application scenario illustrating the range of tasks addressable with such a system has been presented. Position-based admittance-controllers bilaterally exchanging forces between corresponding systems (FaFa-architecture) were used for the haptic subsystem. Therefore, the haptic subsystem consisted of two single-user systems that interacted over a common object, see also Fig. 1.

In this work, we investigate properties of coordinating controllers inserted between the two single-user systems. The controllers implement a virtual coupling, which enhances coordination of the two systems. In section 2 we introduce the new controller before performing a robust stability analysis in section 3. Finally, conclusions are drawn taking into account results of a performance evaluation described in detail in [8], and an outlook on future work is given.

2 Coordinating Controller

Local position-based admittance controllers are used to control haptic interfaces and teleoperator arms. The control structure is well suited for admittance-type devices with non-negligible dynamics, e.g. high mass and friction [9]. Here, we use a control architecture which couples two position-based admittance controllers by implementing a bilateral force-force exchange (FaFa), see Fig. 2. This control structure offers a high performance while also allowing easy parametrization due to the small number of tunable parameters [10].

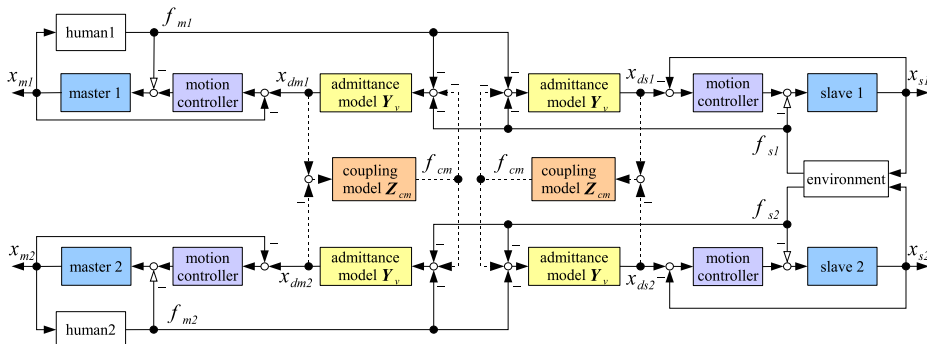


Figure 2: Control architecture of the multi-user teleoperation system. As coordinating controller a virtual coupling via the impedance \mathbf{Z}_{cm} is introduced.

The measured forces f_{m1} and f_{s1} are summed up and used as input for admittance filters of master 1 and slave 1, whereas f_{m2} and f_{s2} are summed up and used as input for admittance filters of master 2 and slave 2. The admittance filters \mathbf{Y}_v are given by

$$\mathbf{Y}_v = \frac{1}{m_d s^2 + b_d s}, \quad (1)$$

where m_d represents the virtual mass and b_d the virtual damping. Inner position control loops are used to drive the devices to desired positions which are obtained as outputs of the admittance filters.

The coordinating controllers in Fig. 2 are marked by dashed lines. They are added to enhance task performance and improve stability of the overall multi-user system by influencing the relative motion between the two master and slave systems. More specifically, the controllers are introduced to prevent undesired asynchronous movements of the two operators, as only synchronized movements lead to a successful task completion in a joint manipulation task. Therefore, movement of one operator is indicated to the other operator by a force in the appropriate direction.

The controllers are implemented as impedance filters \mathbf{Z}_{cm} , i.e. as virtual spring-damper coupling

$$\mathbf{Z}_{cm} = b_{cm} s + c_{cm} \quad (2)$$

between the two single-user systems, where b_{cm} and c_{cm} represent damping and stiffness respectively. In the following we consider a damper only, i.e. $c_{cm} = 0$. In this case, the virtual coupling only generates a force if there is a difference in the velocities of the two systems. Thus, a variable relative position of the end-effectors is possible³.

³ If a spring were used in addition to or instead of the damper there would be a fixed relative equilibrium point of the two end-effectors.

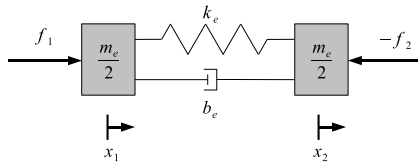


Figure 3: Model of environment

Table 1: Parameters used for the stability analysis

K_p	7500 N/m	m_h	5 kg
K_d	$2\sqrt{7500}$ N s/m	b_h	6 N s/m
b_{cm}	100 N s/m	k_h	40 N/m
T_s	0.0015 s		
T_m	0.0003 s		

3 Stability Analysis

Several plant parameters of a teleoperation system, specifically parameters related to the operators and environment are not fixed but can instead vary greatly. Therefore, a robust stability analysis is performed to determine stability boundaries for the given system with and without coordinating controller. To this end, the parameter space approach, described in detail in [11] and applied to a teleoperation system in [10], is used. The parameter space approach is based on the boundary crossing theorem of polynomials. Boundaries in the s -plane are mapped into the desired parameter space. Thereby, the parameter space is partitioned into several subspaces. By performing a stability test for one parameter set within such a subspace stability of the complete subspace can be determined. In the following the models used for the different subsystems are given, and results of the stability analysis are shown.

To be able to apply the stability analysis to a system with multiple degrees of freedom, dissimilar kinematics, and different dynamics on master and slave side, we assume and implement well tuned computed torque controllers with gravity compensation for the teleoperator arms and haptic interfaces. Therefore, these devices are modeled as masses of 1 kg only. A PD-controller with proportional gain K_p and derivative gain K_d is used to compensate for modeling errors.

As environment we use a mass-spring-damper system, where the mass is lumped on either side of the environment, see Fig. 3.

The interaction forces with the environment are given by

$$F_{s1} = (k_e + b_e s)(X_{s1} - X_{s2}) + \frac{m_e}{2} s^2 X_{s1}, \quad (3)$$

$$F_{s2} = (k_e + b_e s)(X_{s2} - X_{s1}) + \frac{m_e}{2} s^2 X_{s2}, \quad (4)$$

where m_e , b_e , and k_e are the mass, viscous damping, and stiffness of the environment. The interaction forces at the slave end-effectors are denoted $F_{s1/2}$ while the positions of the two slaves are $X_{s1/2}$.

The operators are modeled as passive impedance and additional exogenous force. Interaction forces $F_{m1/2}$ at the master end-effectors are determined as

$$F_{m1} = \alpha(k_h + b_h s + m_h s^2)X_{m1} + F_1^*, \quad (5)$$

$$F_{m2} = \alpha(k_h + b_h s + m_h s^2)X_{m2} + F_2^*, \quad (6)$$

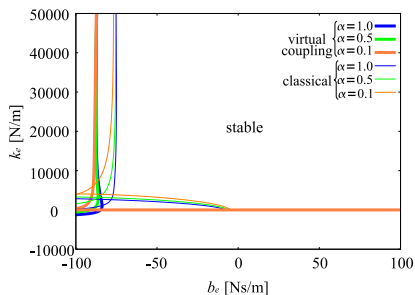


Figure 4: Stability boundaries in the k_e - b_e plane for $m_e = 1$ kg ($m_d = 5$ kg, $b_d = 10$ Nsm $^{-1}$).

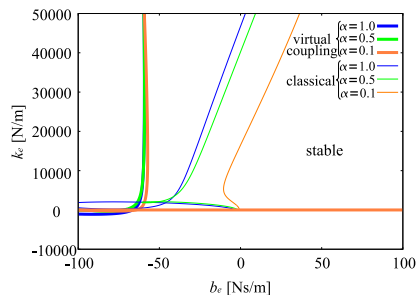


Figure 5: Stability boundaries in the k_e - b_e plane for $m_e = 1$ kg ($m_d = 0.5$ kg, $b_d = 1$ Nsm $^{-1}$).

where k_h , b_h , and m_h are stiffness, damper and mass of the human arm and F_1^* and F_2^* are the exogenous forces applied by the two operators. The factor α is varied in the stability analysis to account for the variability in the human-arm impedance. Here, the same value of α is used for both operators⁴. Sensor dynamics of the force-torque sensors and actuator dynamics are also taken into account. The dynamics are approximated by first-order low-pass filters with time constants T_s and T_m respectively. Table 1 shows the fixed parameters used in the stability analysis. The parameters for the human arm model were hereby taken from previous work [10] and the low-level controller parameters were tuned for good position tracking. The same controller parameters were also used in the evaluation which is described in detail in the complementary paper [8].

Using the models given above, a robust stability analysis was performed, and stable regions were determined in the parameter space. Fig. 4 and Fig. 5 depict the stability region in the k_e - b_e plane for different parameters of the virtual admittance. A variation of the operator impedance was taken into account by different values of α (0.1, 0.5, 1.0). To increase readability of the plots, the influence of m_e on the results is not shown⁵.

In Fig. 4 the system is robustly stable (with respect to variations in human and environment) for all positive values of damping b_e , independently of the virtual coupling. However, a larger stability region, i.e. a more robustly stable system is achieved with virtual coupling activated. In Fig. 5, where smaller values are chosen for the parameters of the virtual admittance, this is even clearer. For a stiff environment (large k_e) some damping b_e of the environment is necessary in case no virtual coupling is provided.

⁴ The stability analysis was also performed with two independent values, but no qualitative difference was observed.

⁵ No qualitative difference was observed when varying m_e between 0.1 kg and 10 kg.

4 Conclusion

In this paper, a new coordinating controller for a multi-user teleoperation system was proposed. The damping-based controller was inserted between two single-user teleoperation systems. A robust stability analysis showed enlarged stability regions for the resulting system. An experimental evaluation of the proposed approach was performed in [8]. There, a significantly higher task performance and efficiency could be determined if the coordinating controller was active.

Summarizing, it can be concluded that the proposed controller results in a more robustly stable system, while at the same time enhancing performance. Future work will focus on extending the proposed scheme to rotational degrees of freedom. Moreover, a more general impedance will be considered, and effects on transparency will be examined.

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