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Enhanced Haptic Teleoperation of Kinematically Dissimilar Motion Systems by Workspace Coordinate Matching

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1 Introduction

Teleoperation, which is concerned with the remote control of robots is a remarkable example of how robotic technology could offer great potential to overcome the natural limitations of the human body. As many researches have been conducted on master-slave systems, various promising applications have been conceived to extend the manipulation skills of the human operator to remote or inaccessible locations. However, most of these applications involve the use of considerably dissimilar structure for master and slave robots. In this context, the present work is concerned with the design of original control strategies to achieve transparent and stable teleoperation of kinematically dissimilar master-slave systems dealing with heterogeneous length, force and power scales. The contribution of this thesis are summarized below.

2 Design of a Versatile Haptic Device

The first part of the present work was devoted to the development of a universal haptic device for real world bilateral teleoperation.

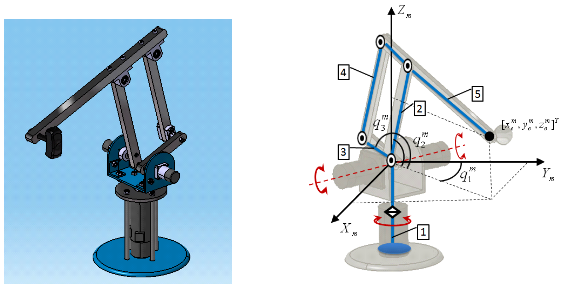

Fig 1: CAD model of the haptic robot

Based on kinematic, dynamic, and workspace criteria, a versatile 3 DOF haptic device that provides enhanced manipulation capabilities to the human operator was designed. The performance of this master robot was analyzed and discussed It was found out that the proposed structure offers promising features that have proved to be useful in achieving transparent and intuitive teleoperation.

3 Four Channel Bilateral Control

Within the general framework of haptic teleoperation, fundamental control techniques and performance evaluation tools were presented and used throughout this work. Accordingly, it was suggested that a four-channel control architecture transmitting position and force information bidirectionally is well suited for our applications. In addition, force and position scaling factors can be implemented to better adapt length and force scales of both master and slave robots and achieve significant position and force tracking.

$$\alpha x_m - x_s = 0 \tag{1}$$

$$\beta f_m + f_s = 0 \tag{2}$$

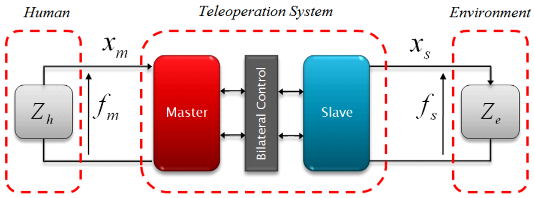

Fig 2: Teleoperation system modeled by a two-port network

The original approach in our contribution also relies on the implementation of torque and force observers to achieve haptic reflection and force feedback without using force sensors. Finally, the critical issues of friction compensation and real-time network communication have been investigated.

The results and guidelines thus provided have been practically applied to the control of teleoperation systems in which they are combined with original control techniques to overcome the kinematic dissimilarity existing between master and slave robots.

4 Task-Oriented Bilateral Control

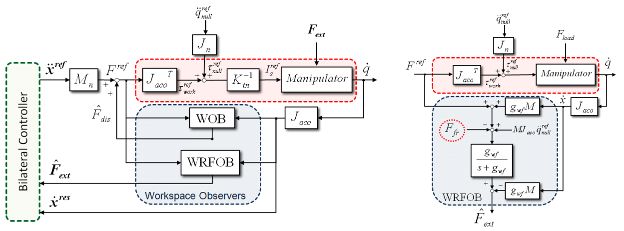

Fig 3: Task-oriented bilateral control with workspace force observer

In the context of teleoperation with kinematically dissimilar master-slave robots, we developed an original control architecture to provide workspace coordinate matching between heterogeneous systems [1].

The main contribution in this approach was the successful application of a task-oriented control scheme to balance the effects of the kinematic dissimilarities. By analyzing the control architecture in terms of operational space variables, it was shown that the proposed controller, which does not require kinematic transformations, effectively improves the stability of the overall system by reducing the kinematic dependencies.

$$\boldsymbol{F}^{ref} = \boldsymbol{M}_n \ddot{\boldsymbol{x}}^{ref} \tag{3}$$

$$\boldsymbol{\tau}^{ref} = \boldsymbol{J}_{aco}^T(\boldsymbol{F}^{ref} + \hat{\boldsymbol{F}}_{dis}) + \boldsymbol{\tau}_{null}^{ref} \tag{4}$$

with $$\boldsymbol{\tau}_{null}^{ref} = \boldsymbol{J}_n \ddot{\boldsymbol{q}}_{null}^{ref} \tag{5}$$

Accordingly, the development of the proposed workspace based bilateral control structure using an arbitrary selected equivalent mass matrix $\boldsymbol{M}_n$ has demonstrated that the joint space torque reference can be synthesized from the acceleration reference in task space without computing the inverse jacobian matrix.

Additionally, to avoid torque/force transformations, a novel workspace reaction force observer (WRFOB) was proposed to estimate external forces acting on the system.

Consequently, by describing the control structure according to the operational space formulation, we have significantly reduced kinematic dependencies, thus leading the way to successful bilateral control with dissimilar structures.

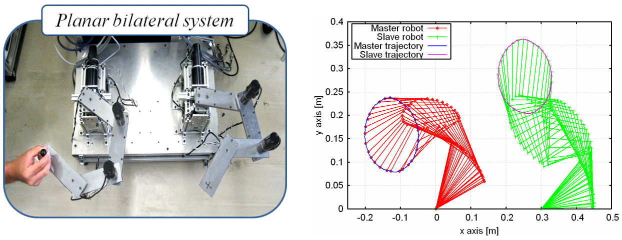

Fig 4: Experimental results for dissimilar master-slave systems

Experimental results supported the theoretical background of the task-oriented control framework and displayed accurate position and force tracking whatever the degree of redundancy of the robots.

Therefore, the proposed task-oriented bilateral control strongly improves the stability of the overall system by workspace disturbance rejection.

5 Hybrid Teleoperation of Mobile Manipulators

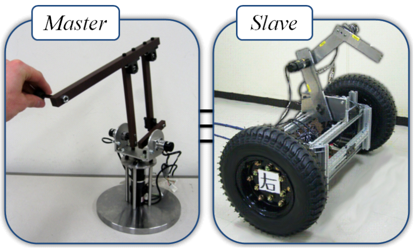

Fig 5: Teleoperation of a two-wheel mobile manipulator

The second approach investigated in this work presents a clear guideline to the teleoperation of mobile slave robots. In that case, it was observed that the traditional position control scheme was unable to control the slave robot with infinite mobility. The critical issue addressed here is concerned with the design of an adequate controller to successfully explore the infinite slave workspace with a ground-based haptic device.

In order to provide infinite workspace capabilities, a hybrid control algorithm is proposed to allow full operability of the mobile slave robot with respect to the ground based haptic device [2]. Accordingly, the switching control architecture successively allows position control and rate control of the slave mobile robot as

$$\ddot{\boldsymbol{x}}_m^{ref} = (\boldsymbol{I} - \boldsymbol{S})\ddot{\boldsymbol{x}}_m^{joy} + \boldsymbol{S}\ddot{\boldsymbol{x}}_m^{bil} \quad (6)$$

$$\ddot{\boldsymbol{x}}_s^{ref} = (\boldsymbol{I} - \boldsymbol{S})\ddot{\boldsymbol{x}}_s^{joy} + \boldsymbol{S}\ddot{\boldsymbol{x}}_s^{bil} \quad (7)$$

where $\boldsymbol{S}$ is a diagonal switching matrix.

Hence, in rate control mode, the human operator defines the velocity of the end effector of the slave robot via manipulating the haptic device.

$$\ddot{\boldsymbol{x}}_s^{joy} = K_v[K_{joy}(\boldsymbol{x}_m^{res} - \boldsymbol{x}_m^{init}) - \dot{\boldsymbol{x}}_s^{res}] \quad (8)$$

Simultaneously, an impedance controller is implemented in the master robot to smoothly guide the master device back to its origin.

$$\ddot{\boldsymbol{x}}_m^{joy} = M_d^{-1}[-D_d\dot{\boldsymbol{x}}_m^{res} - K_d(\boldsymbol{x}_m^{res} - \boldsymbol{x}_m^{init}) + \boldsymbol{F}_{ext}] \quad (9)$$

On the other hand, bilateral control mode enables accurate position and force tracking with respect to the scaling factors.

$$\ddot{x}_m^{bil} = C_p(x_s - \alpha x_m) - C_f(\beta\hat{f}_m + \hat{f}_s) \quad (10)$$

$$\ddot{x}_s^{bil} = C_p(\alpha x_m - x_s) - C_f(\beta\hat{f}_m + \hat{f}_s) \quad (11)$$

Additional control topics related to the use of a dynamically unstable structure for the slave robot were investigated and implemented to the control system. In particular, successful control strategies to achieve posture stabilization and reaction torque estimation in the passive joint were proposed in this research

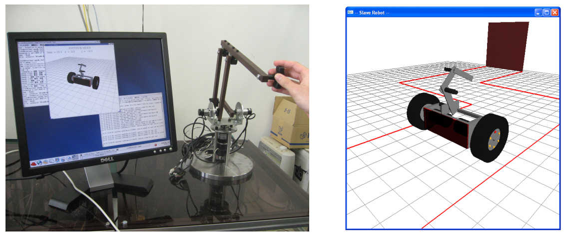

Fig 6: Experimental setup with a virtual slave robot

Experimental results involving a virtual model of the slave mobile robot verified the feasibility of the control architectures proposed in this thesis. Later, the experiment was extended to real world interactions with the actual slave manipulator shown in Fig. 5.

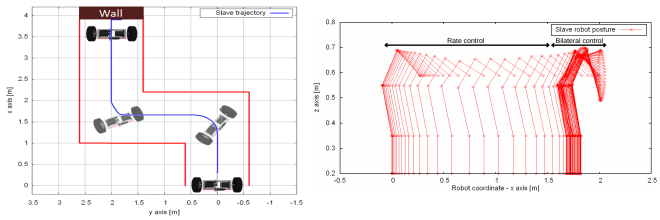

Fig 7: Trajectory and posture attitude of the mobile robot

6 Conclusion

This thesis presented a valuable framework on the control of bilateral robot systems with dissimilar characteristics. The motion systems considered in this research differ not only in terms of position and force scales but also in their kinematic features. Especially, having asymmetrical degrees-of-freedom for both robots is an interesting characteristic that enables enhanced manipulability but drastically complicates the control algorithm.

In order to cope with the kinematic heterogeneity, effective control algorithms have been proposed in a large range of possible master-slave configurations depending on the degree of dissimilarity existing between the two robots. Our goal was to develop a panel of control techniques applicable to a wide variety of teleoperation systems that can be profitable to robotic engineers in the future.

References

[1] A. Lasnier and T. Murakami: "Workspace Based Force Sensorless Bilateral Control with Multi-Degree-of-Freedom Motion Systems ", *Proceedings of the 11th Int. Conf. AMC '10*, pp. 583-588, 21-24 Mar. 2010

[2] A. Lasnier and T. Murakami: "Hybrid Sensorless Bilateral Teleoperation of Two-Wheel Mobile Manipulator with Underactuated Joint", *Proceedings of the IEEE Int. Conf. AIM '10*, 6-9 Jul. 2010