The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Dual-master Teleoperation Control of Kinematically Redundant Robotic Slave Manipulators

Pawel Malysz and Shahin Sirouspour

***Abstract*— Kinematically redundant robotic manipulators (KRRM) can provide a great degree of flexibility for working in complex unstructured environments. Teleoperation control of KRRM requires a strategy to resolve the redundancy of the slave robot while achieving transparency in the task space. In this paper, a two-master control approach is proposed in which the first master transparently controls the redundant slave end-effector in the task space, denoted as the *primary task*. Meanwhile, a second master exploits the slave redundancy to perform a *secondary task* such as obstacle avoidance or internal position control. Kinematic redundancy is considered for the slave robot and the traditional autonomous null-space control approach is also accommodated. Teleoperation control is achieved in two steps. First, velocity-level redundancy resolution is attained through new joint-space Lyapunov-based adaptive motion/force controllers. Coordinating reference commands for the joint-space controllers are designed to give priority to the primary task and decoupling between the tasks is achieved without the use of a dynamically consistent pseudo-inverse. Experimental results with two identical planar two-degree-of-freedom master devices controlling a simulated four-degree-of-freedom redundant slave robot show the effectiveness of the approach.**

***Index Terms*— Teleoperation, Telemanipulation, Cooperative Teleoperation, Redundancy, Multiple Robot Teleoperation, Transparency, Adaptive Control, Nonlinear Control.**

I. INTRODUCTION

Kinematically redundant robotic manipulators (KRRM) are suitable for navigation and work in unstructured environments. Their redundancy can be exploited to achieve multiple task objectives at the same time [1]. Teleoperation applications involving complex environments such as robotic-assisted surgery and space robotics can benefit from manipulator redundancy. Although autonomous control of the slave redundancy in teleoperation is feasible, it might not be effective or practical in many applications. The very same arguments made in support of teleoperation over autonomous control of robots can also be applicable to the problem of redundancy resolution. Humans are usually better than autonomous robots in operating in complex unstructured environments by using their intelligence, experience, and effectively fusing multiple sources of sensory inputs. To capitalize on such human capabilities, in this paper a secondary master device is proposed to manipulate a redundant slave robot in its nullspace by controlling a virtual point on the slave robot. The secondary control point, for example, can help prevent collisions in complex/cluttered environments, avoid sensitive areas of the patient body in a surgical procedure, position the mobile base of a redundant slave, or adjust the robot internal configuration to improve visibility. In the proposed approach, such *secondary* tasks are carried out without interfering with the primary task at the end-effector which is controlled by the primary master device.

The addition of the secondary master device creates an asymmetrical teleoperation system in which two master robots control one slave robot. Examples of multiple master/ multiple slave teleoperation have been previously considered in the literature. Multiple Master Single Slave (MMSS) [2], [3] and Multiple Master Multiple Slave (MSMS) [4], [5] systems can result when cooperative teleoperation tasks among multiple users are of interest. Single Master Multiple Slave (SMMS) systems can be useful when grasping and additional force are required for teleoperated tasks [6], [7]. Redundancy in teleoperation has also been previously explored. However much of the pertinent literature in this area concerns Single Master Single Slave (SMSS) systems where autonomous redundancy resolution is attained through the optimization of local objectives either at the master or slave end. Examples of such objectives include singularity avoidance [8], collision avoidance [9], slave internal position regulation [10] or other sub-task goals as in [11].

There have been a few papers concerning redundancy resolution in teleoperation by involving the human operator. Rubi et al. proposed engaging the user in a singularity avoidance scheme by providing vibrational haptic feedback proportional to singularity closeness [8]. Stanczyk et al. allowed the operator to control the slave nullspace in a unilateral way [12] via user elbow angle tracking to control the remaining slave dof using an augmented task-space approach. Park and Khatib considered teleoperation control of a mobile slave manipulator [13]. The end-effector and mobile base positions were controlled independently such that base motion would not affect end-effector motion.

This paper considers a dual-master system controlling a single redundant slave. A primary master is designated to transparently control the slave end-effector in a bilateral teleoperation configuration. A secondary master (partially) controls the nullspace of the slave manipulator to perform secondary tasks by positioning a virtual point on the robot. A control framework is proposed for co-ordinated control of such a teleoperation system that aims to decouple the primary and secondary task spaces. Performance objectives

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

Pawel Malysz is a doctoral student in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada. MALYSZP@MCMASTER.CA

Shahin Sirouspour is an Associate Professor in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada. SIROUSPOUR@ECE.MCMASTER.CA

in the primary task are position and force tracking between the corresponding master and slave robots as in conventional teleoperation. The aim in the secondary task is to establish position tracking between the secondary master and the virtual control point on the slave and to shape the mechanical impedance presented to the user. Moreover, the secondary task should not affect the primary operation.

To deal with dynamic uncertainty and nonlinear robot dynamics a Lyapunov-based adaptive control approach is employed. Such a strategy has been successfully used before for SMSS symmetric dof teleoperation systems [14], [15]. In this paper joint-space adaptive controllers utilizing velocity-level redundancy resolution are proposed to control the redundant manipulator by augmenting the approach of Lozano and Brogliato [16]. In particular, the adaptive controllers presented in this paper are modified to incorporate a secondary task, its associated nullspace and its decoupling from the primary task. Unlike the force-level redundancy resolution approach used in [13], the velocity-level redundancy resolution method presented here avoids decomposing the robot dynamics into task/posture sub-dynamics. It also eliminates the need for an inertia weighted pseudo-inverse which would require an exact knowledge of the robot mass matrix.

In the proposed controllers any arbitrarily weighted pseudo-inverse may be used. Priority is given to the primary task by controlling the secondary task through the primary's nullspace velocities. Any left-over degree of motion in the nullspace can be autonomously controlled. The ability to handle extra redundancy allows our control framework to handle asymmetries in dof between the combined dof of the primary/secondary task-spaces and the dof of the redundant slave.

Teleoperation transparency in the primary task-space is achieved using a similar approach to that in [14], but using simpler teleoperation coordinating signals. Perfect position tracking is attained between the secondary master and an arbitrary secondary control point on the slave. Haptic feedback is provided through the secondary master device in the form of an adjustable virtual tool impedance Controller stability is proven by assuming i) rigid-body robot dynamics and ii) linear-time-invariant (LTI) second-order models of the user dynamics and environment. In this paper, the results for the case of delay-free teleoperation are presented for applications in which the master/slave robots are in close proximity.

In summary the main contributions of this paper are: i) a new control framework to handle kinematic redundancy in a dual-user/redundant slave teleoperation configuration, ii) user teleoperation control of the slave redundancy with associated secondary task objectives, and iii) the development of stable Lyapunov-based adaptive controllers for achieving the decoupled primary/secondary task-space teleoperaton objectives. The rest of the paper is organized as follows. The dynamics of master and slave systems are discussed in Section II. The proposed controller is presented in Section III. Teleoperation experiments are provided in Section IV. The paper is concluded in Section V.

II. DYNAMICS OF MASTER/SLAVE SYSTEMS

A. Master/Slave Robots

The master/slave devices are n_γ dof robots with joint space dynamic models having the following general nonlinear form [17]:

$$M_\gamma(q_\gamma)\ddot{q}_\gamma + C_\gamma(q_\gamma, \dot{q}_\gamma)\dot{q}_\gamma + G_\gamma(q_\gamma) = \tau_\gamma - \tau_{e,\gamma} \quad (1)$$

where $\gamma = 1m$ for the primary master, $\gamma = 2m$ for the secondary master, $\gamma = s$ for the slave, q_γ a joint configuration vector, τ_γ joint control forces/torques and $\tau_{e,\gamma}$ joint forces/torques corresponding to external forces/torques. $M_\gamma(q_\gamma)$ is a positive definite mass matrix, $C_\gamma(q_\gamma, \dot{q}_\gamma)$ represents velocity dependent elements such as Coriolis and centrifugal effects, $G_\gamma(q_\gamma)$ corresponds to position-dependent forces such as gravity.

B. Master systems incorporating operators

The end-effectors of the non-redundant master robots are chosen as their task-space control points and denoted as vectors x_{1m} for the primary master and x_{2m} for the secondary master. Both these satisfy the velocity relationships shown in (2) where J_{1m} and J_{2m} are configuration dependant, full rank square Jacobian matrices.

$$\dot{x}_{1m} = J_{1m}\dot{q}_{1m} \in \Re^{n_{1m}}, \quad \dot{x}_{2m} = J_{2m}\dot{q}_{2m} \in \Re^{n_{2m}} \quad (2)$$

The external forces on the master robots correspond to hand forces at the end-effectors, to simplify the design and analysis, the operator dynamics are assumed to be second-order LTI models in the task-spaces.

$$\tau_{e,im} = -J_{im}^T f_{ih}, \quad f_{ih} = f_{ih}^* - M_{ih}\ddot{x}_{im} - B_{ih}\dot{x}_{im} - K_{ih}[x_{im} - x_{im}^\circ] \quad (3)$$

where $i = 1$ for the primary master and $i = 2$ for the secondary master. M_{ih}, B_{ih}, and K_{ih} are symmetric positive definite matrices corresponding to mass, damping, stiffness, x_{im}° represent the contact points of each hand and f_{ih}^* are the human exogenous forces subject to

$$\|f_{ih}^*\|_\infty \leq \quad \alpha_{ih} < +\infty, \quad \alpha_{ih} > \quad 0 \quad (4)$$

Using (1), (2) and (3) the combined dynamics of the primary ($i = 1$) and secondary ($i = 2$) master systems of dimension n_{im} can be represented by (5).

$$\mathcal{M}_{im}\ddot{q}_{im} + \mathcal{C}_{im}\dot{q}_{im} + \mathcal{G}_{im} = \tau_{im} + J_{im}^T f_{ih}^* \in \Re^{n_{im}} \quad (5)$$

$$\mathcal{M}_{im} = M_{im}(q_{im}) + J_{im}^T M_{ih} J_{im} \in \Re^{n_{im} \mathrm{x} n_{im}}$$

$$\mathcal{C}_{im} = C_{im}(\dot{q}_{im}, q_{im}) + J_{im}^T M_{ih}\dot{J}_{im} + J_{im}^T B_{ih} J_{im} \in \Re^{n_{im} \mathrm{x} n_{im}}$$

$$\mathcal{G}_{im} = G_{im}(q_{im}) + J_{im}^T K_{ih}[x_{im} - x_{im}^\circ] \in \Re^{n_{im}}$$

C. Slave system incorporating environment

The end-effector of the redundant slave robot is chosen as the primary task-space control point and is denoted by vector x_{1s}. Since the primary master dof is less than the dof of the slave robot ($n_{1m} < n_s$) an arbitrary internal secondary control point is chosen to resolve redundancy; this task-space vector is denoted as x_{2s}. The workspace velocities for the primary and secondary control points can be obtained from the following relations

$$\dot{x}_{1s} = J_{1s}\dot{q}_s \in \Re^{n_{1m}}, \qquad \dot{x}_{2s} = J_{2s}\dot{q}_s \in \Re^{n_{2m}} \tag{6}$$

where J_{1s} and J_{2s} are configuration dependant full rank Jacobian matrices. The external forces/torques are environment forces at the slave robot end-effector as shown in (7) where a second-order LTI model in the primary task-space is used.

$$\tau_{e,s} = J_{1s}^T f_e, \qquad f_e = M_e\ddot{x}_{1s} + B_e\dot{x}_{1s} + K_e[x_{1s} - x_{1s}^\circ] \tag{7}$$

Here M_e, B_e, and K_e are symmetric positive definite matrices corresponding to mass, damping, stiffness, and x_{1s}° represents the contact point of the environment.

Using (1), (6) and (7) the dynamics of the slave system in joint-space coordinates are governed by

$$\mathcal{M}_s\ddot{q}_s + \mathcal{C}_s\dot{q}_s + \mathcal{G}_s = \tau_s \in \Re^{n_s} \tag{8}$$

$$\mathcal{M}_s = M_s(q_s) + J_1^T M_e J_1 \in \Re^{n_s \text{x} n_s}$$
$$\mathcal{C}_s = C_s(\dot{q}_s, q_s) + J_1^T M_e \dot{J}_1 + J_1^T B_e J_1 \in \Re^{n_s \text{x} n_s}$$
$$\mathcal{G}_s = G_s(q_s) + J_1^T K_e[x_{1s} - x_{1s}^\circ] \in \Re^{n_s}$$

III. CONTROL DESIGN

The design of the controllers are performed in three stages. The first stage introduces the joint-space adaptive controllers that can ensure joint tracking in the presence of model uncertainty. The second stage shows the local redundancy resolution strategy and decomposes the control from joint-space to task-space. The third stage shows the desired task-space control for teleoperation. The last subsection addresses stability.

A. Adaptive Master/Slave Controllers

The local adaptive control laws are introduced in (9) where they contain adaptive model-based feedforward compensation ($Y_\gamma\hat{\Theta}_\gamma$) plus feedback control ($\mathcal{K}_\gamma\rho_\gamma$).

$$\tau_\gamma = Y_\gamma\hat{\Theta}_\gamma + \mathcal{K}_\gamma\rho_\gamma + \alpha_\gamma \in \Re^{n_\gamma}, \quad \rho_\gamma \triangleq \dot{q}_\gamma^r - \dot{q}_\gamma \in \Re^{n_\gamma} \tag{9}$$

$$\alpha_\gamma \triangleq \begin{cases} J_{im}^T \alpha_{ih}\text{sign}(J_{im}\rho_{im}), & \gamma = im \\ 0, & \gamma = s \end{cases} \tag{10}$$

Here $\dot{q}_\gamma^r$ are joint command vectors to be introduced later, $\mathcal{K}_\gamma > 0$ diagonal matrices, and ρ_γ a type of tracking error. In (9), $\hat{\Theta}_\gamma$ denotes the estimate of constant Θ_γ which contains all unknown parameters of the primary master ($\gamma = 1m$), secondary master ($\gamma = 2m$) and slave ($\gamma = s$) subsystems. Furthermore, regressor matrices $Y_\gamma(q_\gamma, \dot{q}_\gamma, \dot{q}_\gamma^r, \ddot{q}_\gamma^r)$ are defined based on the so-called linear-in-parameter formulation of robot dynamics [17], i.e.

$$Y_\gamma(q_\gamma, \dot{q}_\gamma, \dot{q}_\gamma^r, \ddot{q}_\gamma^r)\hat{\Theta}_\gamma = \hat{\mathcal{M}}_\gamma(q_\gamma)\ddot{q}_\gamma^r + \hat{\mathcal{C}}_\gamma(q_\gamma, \dot{q}_\gamma)\dot{q}_\gamma^r + \hat{\mathcal{G}}_\gamma(q_\gamma) \tag{11}$$

The sign term in (10) is added to deal with the unknown but bounded exogenous force f_{ih}^*. In practice to avoid chattering in control, f_{ih}^* can be included in the parameter vector and adapted for. This usually provides satisfactory results if the rate of adaptation is much faster than the changes in exogenous force. The parameter adaptation laws are governed by

$$\dot{\hat{\Theta}}_{\gamma k} = \begin{cases} 0, & \hat{\Theta}_{\gamma k} \le \Theta_{\gamma k}^- \text{ and } Y_{\gamma k}^T\rho_\gamma \le 0 \\ 0, & \hat{\Theta}_{\gamma k} \ge \Theta_{\gamma k}^+ \text{ and } Y_{\gamma k}^T\rho_\gamma \ge 0 \\ \Gamma_{\gamma k} Y_{\gamma k}^T \rho_\gamma, & \text{otherwise} \end{cases} \tag{12}$$

where γk denotes the kth parameter of either primary master ($\gamma = 1m$), secondary master ($\gamma = 2m$) or slave ($\gamma = s$). Γ_γ represents a parameter update gain vector with elements $\Gamma_{\gamma k} > 0$, $\Theta_{\gamma k}^-$ and $\Theta_{\gamma k}^+$ denote the minimum and maximum allowable values of $\Theta_{\gamma k}$, and $\tilde{\Theta}_\gamma = \hat{\Theta}_\gamma - \Theta_\gamma$ represents parameter estimate error vector.

Using the candidate Lyapunov function in (13) one can obtain (14) where (5), (8)-(12) and skew-symmetry of $\dot{M}_\gamma - 2C_\gamma$ has been employed.

$$V_\gamma = \frac{1}{2}\rho_\gamma^T \mathcal{M}_\gamma \rho_\gamma + \frac{1}{2}\tilde{\Theta}_\gamma^T \Gamma_\gamma^{-1} \tilde{\Theta}_\gamma \tag{13}$$
$$\dot{V}_\gamma \le -\rho_\gamma^T \mathcal{K}_\gamma \rho_\gamma \tag{14}$$

Finally, using (13) and (14) it can be concluded

$$\rho_s \in L_2 \cap L_\infty, \quad \rho_{1m} \in L_2 \cap L_\infty, \quad \rho_{2m} \in L_2 \cap L_\infty \tag{15}$$

B. Local Master/Slave Joint Command Vectors

To control the task positions x_{1m} and x_{2m} the joint command vectors for the masters are defined in (16) yielding (17) where $i = 1, 2$.

$$\dot{q}_{im}^r \triangleq J_{im}^{-1}\dot{x}_{im}^r \tag{16}$$
$$\bar{\rho}_{im} \triangleq J_{im}\rho_{im} = \dot{x}_{im}^r - \dot{x}_{im} \in L_2 \cap L_\infty \tag{17}$$

Here $\dot{x}_{1m}^r$ and $\dot{x}_{2m}^r$ are task-space command vectors to be introduced later.

The slave task-space positions x_{1s} and x_{2s} must also be controlled. Since the slave robot is kinematically redundant, a velocity-level pseudoinverse redundancy resolution approach is employed. To this end, the following notations are defined

$$J_\chi^+ = W_\chi^{-1} J_\chi^T (J_\chi W_\chi^{-1} J_\chi^T)^{-1} \tag{18}$$
$$N_\chi = I - J_\chi^+ J_\chi \tag{19}$$
$$\dot{x}_{2|1s} = J_{2|1s}\dot{q}_s = \dot{x}_{2s} - J_{2s}J_{1s}^+\dot{x}_{1s}, \quad J_{2|1s} = J_{2s}N_{1s} \tag{20}$$

where $\chi = 1s,\ 2|1s$, J_χ^+ is a pseudoinverse for the full rank matrix J_χ weighted by the positive definite matrix W_χ, N_χ a nullspace projector and $\dot{x}_{2|1s}$ denotes secondary task-space velocities that lie in the nullspace of the primary task. Using (18)-(20) the slave joint velocities can be decomposed as

$$\dot{q}_s = J_{1s}^+\dot{x}_{1s} + N_{1s}J_{2|1s}^+(\dot{x}_{2s} - J_{2s}J_{1s}^+\dot{x}_{1s}) + N_{1s}N_{2|1s}\dot{q}_{Ns} \tag{21}$$

where $\dot{q}_{Ns} = N_{1s}N_{2|1s}\dot{q}_s$ represents the remaining nullspace velocities. It is now possible to define the slave joint command vector $\dot{q}_s^r$ in an analogous decomposed form

$$\dot{q}_s^r \triangleq J_{1s}^+\dot{x}_{1s}^r + N_{1s}J_{2|1s}^+(\dot{x}_{2s}^r - J_{2s}J_{1s}^+\dot{x}_{1s}^r) + N_{1s}N_{2|1s}\dot{q}_{Ns}^r \tag{22}$$

where $\dot{x}_{1s}^r$, $\dot{x}_{2s}^r$ are slave task-space command vectors to be introduced later and $\dot{q}_{Ns}^r$ is locally designed to resolve any remaining slave redundancy. The term $J_{2s}J_{1s}^+\dot{x}_{1s}^r$ in

(22) is added to compensate for velocities induced into the secondary task-space by primary motion. It is instrumental in achieving decoupling between the primary and secondary task spaces. Subtracting (21) from (22), one can obtain

$$\bar{\rho}_{1s} \triangleq J_{1s}\rho_s = \dot{x}^r_{1s} - \dot{x}_{1s} \in L_2 \bigcap L_\infty \quad (23)$$

$$\bar{\rho}_{2s} \triangleq J_{2s}\rho_s = \dot{x}^r_{2s} - \dot{x}_{2s} \in L_2 \bigcap L_\infty \quad (24)$$

$$\bar{\rho}_{Ns} \triangleq N_{1s}N_{2|1s}\rho_s = N_{1s}N_{2|1s}(\dot{q}^r_{Ns} - \dot{q}_{Ns}) \in L_2 \bigcap L_\infty \quad (25)$$

It should be noted that since the Jacobians, pseudoinverses and nullspace projectors used are only functions of position, the vectors $\dot{q}^r_\gamma$ and $\ddot{q}^r_\gamma$ in (16) and (22) will avoid acceleration measurement provided $\ddot{q}^r_{Ns}$, $\dot{q}^r_{Ns}$, $\ddot{x}^r_l$ and $\dot{x}^r_l$ are designed to avoid acceleration measurement where $\gamma = 1m, 2m$ or s and $l = 1m, 2m, 1s$ or $2s$.

C. Task-space Command Vectors for Teleoperation

The task-space command vectors $\dot{x}^r_{1m}$, $\dot{x}^r_{2m}$, $\dot{x}^r_{1s}$ and $\dot{x}^r_{2s}$ will be designed to achieve the task-space teleoperation objectives of primary/secondary position tracking, primary/secondary virtual tool impedance shaping and primary force tracking while avoiding acceleration and derivative of force measurements. To this end let

$$\dot{x}^r_{1m} = A_1(\tilde{f}_{1h} - \kappa_{f1}\tilde{f}_e) - \Lambda_1\dot{\tilde{x}}_{1m} + \dot{\tilde{x}}_{1m} \quad (26)$$

$$\dot{x}^r_{1s} = \kappa^{-1}_{p1}[A_1(\tilde{f}_{1h} - \kappa_{f1}\tilde{f}_e) - \Lambda_1\dot{\tilde{x}}_{1m} + \dot{\tilde{x}}_{1m}] + \lambda_1(\kappa^{-1}_{p1}x_{1m} - x_{1s}) \quad (27)$$

$$\dot{x}^r_{2m} = A_2\tilde{f}_{2h} - \Lambda_2\dot{\tilde{x}}_{2m} + \dot{\tilde{x}}_{2m} \quad (28)$$

$$\dot{x}^r_{2s} = \kappa^{-1}_{p2}[A_2\tilde{f}_{2h} + (1-\Lambda_2)\dot{\tilde{x}}_{2m}] + \lambda_2(\kappa^{-1}_{p2}x_{2m} - x_{2s}) \quad (29)$$

where A_1, A_2, Λ_1, Λ_2, λ_1, λ_2 are positive diagonal matrices, κ_{p1}, κ_{p2} diagonal motion scaling matrices and κ_{f1} is a diagonal force scaling matrix. If Q is one of the following $\{\dot{x}_{1m}, \dot{x}_{2m}, f_{1h}, f_{2h}, f_e\}$, then the notation $\tilde{Q}$ represents a filtered quantity specified by filter

$$\dot{\tilde{Q}} = CQ - C\tilde{Q} \quad (30)$$

The diagonal matrix C represents the filter bandwidths and ultimately affects the stability, transparency and noise amplification of the teleoperation system. Filtered feedforward force/velocity commands are present in (26)-(29) to facilitate a virtual tool response. Moreover, (27) and (29) contain position errors to ensure position tracking.

Now the transparency of the controllers in the primary task-space will be explored. Substituting (26) into (17), (27) into (23), and using (30) yields

$$\kappa_{p1}\bar{\rho}_{1s} - \bar{\rho}_{1m} = (\dot{x}_{1m} - \kappa_{p1}\dot{x}_{1s}) + \lambda_1(x_{1m} - \kappa_{p1}x_{1s}) \quad (31)$$

$$\bar{\rho}_{1e} \triangleq x_{1m} - \kappa_{p1}x_{1s} \in L_2 \bigcap L_\infty \quad (32)$$

$$\bar{\rho}_{1v} \triangleq \dot{x}_{1m} - \kappa_{p1}\dot{x}_{1s} \in L_2 \bigcap L_\infty \quad (33)$$

$$\tilde{f}_{1h} = \kappa_{f1}\tilde{f}_{1e} + (A_1C)^{-1}\ddot{\tilde{x}}_{1m} + A_1^{-1}\Lambda_1\dot{\tilde{x}}_{1m} + \bar{\rho}_{1f} \quad (34)$$
$$\bar{\rho}_{1f} \triangleq A_1^{-1}\bar{\rho}_{1m} \in L_2 \bigcap L_\infty$$

where the primary task-space position (32) and velocity (33) tracking objectives can be concluded from (31) using Lemma 1 from [14]. From (31) it is seen that the motion tracking performance can be adjusted by the parameter λ_1. The force tracking objective is shown in (34) where an adjustable virtual tool dynamic is present that behaves as a mass-damper link for frequencies below C rad/s. Under quasi-static conditions, the primary user's filtered hand force and filtered environment force would track each other.

For the secondary task-space, substituting (28) into (17), (29) into (24), and using (30) one can obtain

$$\kappa_{p2}\bar{\rho}_{2s} - \bar{\rho}_{2m} = (\dot{x}_{2m} - \kappa_{p2}\dot{x}_{2s}) + \lambda_2(x_{2m} - \kappa_{p2}x_{2s}) \quad (35)$$

$$\bar{\rho}_{2e} \triangleq x_{2m} - \kappa_{p2}x_{2s} \in L_2 \bigcap L_\infty \quad (36)$$

$$\bar{\rho}_{2v} \triangleq \dot{x}_{2m} - \kappa_{p2}\dot{x}_{2s} \in L_2 \bigcap L_\infty \quad (37)$$

$$\tilde{f}_{2h} = (A_2C)^{-1}\ddot{\tilde{x}}_{2m} + A_2^{-1}\Lambda_1\dot{\tilde{x}}_{2m} + \bar{\rho}_{1f} \quad (38)$$
$$\bar{\rho}_{2f} \triangleq A_2^{-1}\bar{\rho}_{2m} \in L_2 \bigcap L_\infty$$

where the secondary task-space position (36) and velocity (37) tracking objectives can be concluded from (35). The secondary master virtual tool response is demonstrated in (38).

D. Stability

This subsection addresses the stability of primary/secondary task teleoperation as well as the local slave redundancy method. These results apply assuming $J_{2|1s}$ is full rank. For simplicity $x^\circ_{1m} = x^\circ_{1s} = 0$ in (3) and (7) is assumed. The non-zero case can easily be handled through appropriate position offset transformations.

Combining (34) with environment model (7) and master operator model (3) and utilizing (30) yield

$$f^*_{1h} + \breve{\rho}_1 = (M_{1h} + \kappa_{f1}M_e\kappa^{-1}_{p1} + (A_1C)^{-1})\ddot{\tilde{x}}_{1m} + (B_{1h} + \kappa_{f1}B_e\kappa^{-1}_{p1} + A_1^{-1}\Lambda_1)\dot{\tilde{x}}_{1m} + (K_{1h} + \kappa_{f1}K_e\kappa^{-1}_{p1})\tilde{x}_{1m} \quad (39)$$

$$\breve{\rho}_1 \triangleq M_e\kappa^{-1}_{p1}\tilde{\bar{\rho}}_{1a} + B_e\kappa^{-1}_{p1}\tilde{\bar{\rho}}_{1v} + K_e\kappa^{-1}_{p1}\tilde{\bar{\rho}}_{1e} - \bar{\rho}_{1f} \quad (40)$$

Using (30) and Lemma 2 from [14] on (39) one can ultimately conclude

$$x_{1m}, x_{1s}, \dot{x}_{1m}, \dot{x}_{1s}, \tilde{f}_{1h}, \tilde{f}_e \in L_\infty \quad (41)$$

Similarly, combining (38) with secondary master operator model (3) and using (30) yields

$$f^*_{2h} + \bar{\rho}_{2f} = (M_{2h} + (A_2C)^{-1})\ddot{\tilde{x}}_{2m} + (B_{2h} + A_2^{-1}\Lambda_2)\dot{\tilde{x}}_{2m} + K_{2h}\tilde{x}_{2m} \quad (42)$$

Using (30) and Lemma 2 from [14] on (42) one can obtain

$$x_{2m}, x_{2s}, \dot{x}_{2m}, \dot{x}_{2s}, \tilde{f}_{2h} \in L_\infty \quad (43)$$

The nullspace command vectors $\dot{q}^r_{Ns}$ should be designed such that one is able to conclude $\dot{q}_{Ns} \in L_\infty$ and $q_{Ns} \in L_\infty$. This will be assured if the design of $\dot{q}^r_{Ns}$ is based on the gradient of some locally convex optimization function of joint configuration. One can subsequently conclude that joint positions and velocities are bounded, i.e. $q_s \in L_\infty$ and $\dot{q}_s \in L_\infty$.

IV. TELEOPERATION EXPERIMENTS

A kinematically redundant dual master single slave platform shown in Fig. 1 has been used to evaluate the proposed teleoperation controller. Two Quanser planar twin-pantograph haptic devices have been employed as the master robots. The pantograph devices are actuated by direct-drive DC motors attached to the proximal links, each motor has max torque output of approximately 0.370 Nm. The motor shaft angles are measured by optical encoders with 20,000 counts per revolution. Two Mini40 force/torque sensors from ATI Industrial Automation have been attached to the mechanisms end-effectors to measure hand forces. The pantograph devices are light, have low friction and are easily backdrivable. The mass of the force sensor and end-effector attachments dominate the device dynamics. Therefore the master robots have been modeled as linear-decoupled mass-spring-damper systems in the workspace co-ordinates. Position-dependent variations in the device dynamics due to nonlinearities are adapted for by the local master controllers. To avoid unwanted chattering, the master controllers were modified such that they would adapt for f_{1h}^* and f_{2h}^* by adding it to the feedforward term (11) and not utilizing (10). The task-spaces for each master robot were chosen as the x-y axes leaving the one redundant dof to be controlled locally. This dof was controlled such that the end-effector orientation remained fixed using local PD control.

The slave robot was simulated as a joint-torque controlled planar four-link mechanism. Each link was modeled as a uniform thin rod of length of 0.1 m, mass of 0.1 kg and moment of inertia $I = 8.33\text{x}10^{-5}\ kg \cdot m^2$. For simplicity gravity and motor dynamics were ignored. To make the model more realistic joint measurements were quantized to 20000 counts/rev, joint torque saturated to 0.3 Nm and Gaussian white noise with standard deviation of 0.05 N added to end-effector force measurement. This makes the actuation and sensing capabilities of the master/slave systems comparable. Also joint friction of 0.02 Nms was also modeled.

Although in principle it is possible to obtain expressions as functions of position and velocity for the derivatives of the pseudoinverses and nullspace projectors used (i.e. derivatives of $J_{1s}^+, N_{1s}J_{2|1s}^+, J_{2s}J_{1s}^+$ and $N_{1s}N_{2|1s}$), a filtered numerical derivative proved effective in the experiments. The slave end-effector was the primary task-space control point. An arbitrary control point was chosen as the secondary task-space. A virtual environment acting on the x-axis was used for experiments and was modeled as a spring with a stiffness of 500 N/m. The slave system and control software were implemented using Matlab RTW Simulink with Quanser Wincon real-time control software at a rate of 2000 Hz. The slave system was visualized using Matlab Virtual Reality toolbox at a display rate of 25 Hz. The control parameters used in the experimental trials are given in Table I.

The experiment places the secondary control point midway on the third link. Experimental results are displayed in Fig. 2 where force and position tracking graphs show the desired tracking objectives. There were three phases in this experiment. In the first phase (0-4.5 sec) the primary master performs free motion while the secondary master holds their control point still. The second phase (4.5-8.1 sec) sees the secondary master perform free motion while the primary master holds still. A bird's eye view of the slave during a portion of these two phases is shown in Fig. 2 c) and f). In the final phase (9.35-13.15 sec) the primary master interacts with the 500 N/m environment while the secondary master holds still. Decoupling can be seen by the lack of movement and forces while the other performs motion/contact. Any movement/forces while a master holds still are due to unintentional effects such as hand tremor, drift and jerk. The sinusoidal like motions were deliberately made to demonstrate force/position tracking. The non-zero forces during free-motion are due to the control rendered intervening tool dynamics.

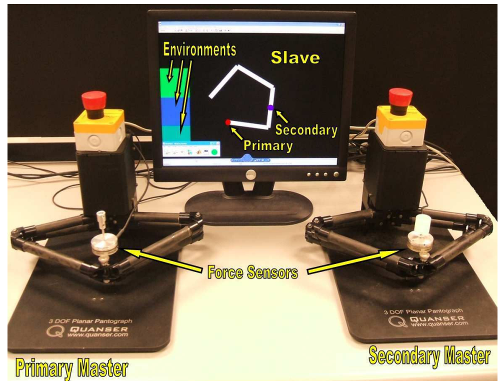

Fig. 1. The experimental setup.

TABLE I
CONTROLLER PARAMETERS

A_1	Λ_1	λ_1	κ_{p1}	κ_{f1}
0.02 $kg^{-1}s$	0.01	30 s^{-1}	1	1
A_2	Λ_2	λ_2	κ_{p2}	C
0.03 $kg^{-1}s$	0.1	15 s^{-1}	0.75	64pi rad/s
$\mathcal{K}_{1m}, \mathcal{K}_{2m}$	$\mathcal{K}_s$	Γ_{1m}, Γ_{2m}	Γ_s	
35 Nsm^{-1}	0.04 Nms	100-2000	0.1-6000000	

V. CONCLUSIONS

While traditional teleoperation considers single master single slave systems with with similar degrees of freedom, this paper explored a multi-robot asymmetric teleoperation platform with slave kinematic redundancy. In the presented dual master (user) single redundant slave system, the masters are designated into a primary master (user) that performs in a way analogous to traditional teleoperation and a second master (user) that controls a secondary task through the nullspace of the primary. Such a scheme would be useful in complex environments where a human user can intelligently perform complex tasks such as collision avoidance or internal position control without disturbing the primary task. The conventional local autonomous redundancy control approaches are also accommodated in the proposed framework and can be employed to control any remaining

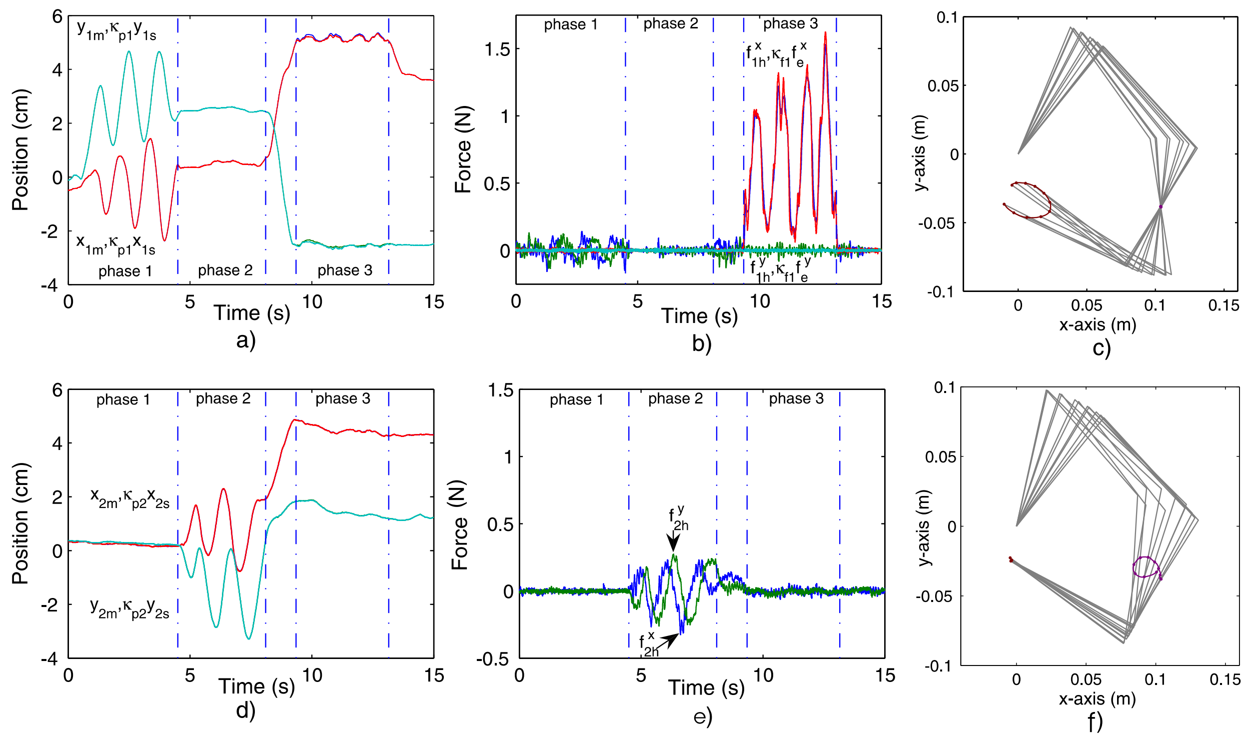

Fig. 2. Teleoperation experimental results; a) primary position tracking b) primary force tracking c) bird's eye view of slave at 0.1 s increments from 3.5 $s-4.5$ s where superimposed are the masters trajectories $\kappa_{p1}^{-1}x_{1m}$ and $\kappa_{p2}^{-1}x_{2m}$; the dots indicate the positions at 0.1 s increments d) secondary position tracking e) secondary master hand forces. f) bird's eye view from 4.5-5.5 s. The experimental phase transitions are indicated by vertical lines and occur at 4.5 s, 8.1 s, 9.35 s and 13.15 s respectively. Note: tracking graphs a) b) and d) actually contain four signals.

kinematic redundancy in the slave system. Adaptive joint-space controllers with local velocity-level redundancy resolution are proposed to achieved the teleoperation objectives and decoupling primary/secondary tasks in the presence of dynamic uncertainty. The proposed method was validated in experiments using a system with two 2DOF master robots and a single simulated 4DOF redundant slave robot. Due to space restrictions this paper only presented a control solution for delay-free teleoperation where the primary and secondary tasks are nonconflicting. A control approach to handle other cases is currently under development.

REFERENCES

[1] R. Patel and F. Shadpey, *Control of Redundant Robot Manipulators*. Berlin: Springer-Verlag, 2005.

[2] S. S. Nudehi, R. Mukherjee, and M. Ghoudoussi, "A shared-control approach to haptic interface design for minimally invasive telesurgical training," *IEEE trans. on Cont. Sys. Tech.*, vol. 13, pp. 588–592, 2005.

[3] B. Khademian and K. Hashtrudi-Zaad, "A four-channel multilateral shared control architecture for dual-user teleoperation systems," in *Proc. IEEE Int. Conf. Intelligent Robots and Systems*, pp. 2660–2666, 2007.

[4] S. Sirouspour, "Modeling and control of cooperative teleoperation systems," *IEEE Transactions on Robotics*, vol. 21, pp. 1220–1225, December 2005.

[5] N. Y. Chong, S. Kawabata, K. Ohba, T. Kotoku, K. Komoriya, K. Takase, and K. Tanie, "Multioperator teleoperation of multi-robot systems with time delay: Part 1-aids for collision free control," *Presence*, vol. 11, pp. 277–291, 2002.

[6] D. Lee and M. Spong, "Bilateral teleoperation of multiple cooperative robots over delayed communication networks:theory," in *Proc. IEEE ICRA*, pp. 360–365, 2005.

[7] G. Hwang, P. Szemes, N. Ando, and H. Hashimoto, "Development of a single-master multi-slave tele-micromanipulation system," *Advanced Robotics*, vol. 21, no. 3-4, pp. 329–349, 2007.

[8] J. Rubi, A. Rubio, and A. Avello, "Involving the operator in a singularity avoidance strategy for a redundant slave manipulator in a teleoperated application," in *Proc. IEEE Int. Conf. Intelligent Robots and Systems*, pp. 2973–2978, 2002.

[9] D. Nanayakkara, K. Kiguchi, T. Murakami, K. Watanabe, and K. Izumi, "Skillful adapatation of a 7-dof manipulator to avoid moving obstacles in a teleoperated force control task," in *Proc. IEEE Conf. ISIE*, pp. 1982–1987, 2006.

[10] J. Jansen, R. Kress, and S. Babcock, "Controller design for a force-reflecting teleoperator system with kinematically dissimilar master and slave," *J. Dynamic Sys. Meas. and Control*, vol. 114, pp. 641–649, 1992.

[11] N. Nath, E. Tatlicioglu, and D. Dawson, "Teleoperation with kinematically redundant robot manipulators with sub-task objectives," in *to appear Proc. IEEE Int. Conf. Decision and Control*, 2008.

[12] B. Stanczyk, A. Peer, and M. Buss, "Development of a high performance haptic telemanipulation system with dissimilar kinematics," *Advanced Robotics*, vol. 20, no. 11, pp. 1303–1320, 2006.

[13] J. Park and O. Khatib, "A haptic teleoperation approach based on contact force control," *Int. J. Robotics Research*, vol. 25, no. 5-6, pp. 575–591, 2006.

[14] W. Zhu and S. Salcudean, "Stability guaranteed teleoperation: an adaptive motion/force control approach," *IEEE Trans. Automat. Contr.*, vol. 45, pp. 1951–1969, November 2000.

[15] P. Malysz and S. Sirouspour, "Nonlinear and filtered force/position mappings in bilateral teleoperation with application to enhanced stiffness discrimination," *IEEE Trans. Robotics*, vol. 25, no. 2, 2009.

[16] R. Lozano and B. Brogliato, "Adaptive hybrid force-position control for redundant manipulators," *IEEE trans. Auto. Control.*, vol. 37, no. 10, pp. 1501–1505, 1992.

[17] L. Sciavicco and B. Siciliano, *Modeling and Control of Robot Manipulators, Second Edition*. Springer-Verlag, 2000.