A Novel Adaptive Bilateral Control Scheme Using Similar Closed-Loop Dynamic Characteristics of Master/Slave Manipulators

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Received 2 June 2000; accepted 23 February 2001

This article presents a novel adaptive bilateral control scheme for obtaining ideal responses for teleoperation systems with uncertainties. A condition that is equivalent to getting an ideal response in teleoperation has been found to be making the closed-loop dynamics of master and slave manipulators a similar form. An adaptive approach is applied to achieve similarity for the uncertain master and slave manipulators. Using the similar closed-loop dynamic characteristics of master/slave teleoperation systems, excellent position and force tracking performance has been obtained without estimating the impedance of human and environment. The validity of the theoretical results is verified by experiments.

1. INTRODUCTION

Teleoperation systems have been extensively studied since the pioneering work of Goertz[1]; these studies have been motivated by a variety of applications, ranging from nuclear operations and space exploration to underwater tasks and medical applications. Recently, with the development of virtual reality, application areas have been extended to the entertainment and training fields.

A teleoperation system consists of a master manipulator, a remotely located slave manipulator, a human operator, and an environment. The human operator applies his/her intentional force to the master manipulator to make the slave perform a series of commands. Generally, the resulting position of the master manipulator is sent to the slave, and the force information sensed by the slave is reflected back to the human operator through the master. If the slave manipulator exactly reproduces the master's motions and the master manipulator accurately transmits the measured slave force, the operator should experience the same sensation that the slave manipulator does. In other words, the teleoperation system would be completely transparent. This has been considered to be an ideal re-

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sponse in terms of evaluating the performance of teleoperation systems.

To evaluate the system performance or to design a new control scheme, several definitions of an ideal response of teleoperation systems have been introduced. Traditionally, a transparency in which operators feel as if they are touching the task directly was considered as the ideal one.

Lawrence defined transparency as that in which the transmitted impedance to a human operator is equivalent to the environmental impedance.[2] H-Zaad mentioned that to achieve transparency, kinematic correspondence should be obtained, as well as impedance matching.[3] This is equivalent to the match between master and slave positions and forces. Hannaford and Yokokohji have also presented this point.[4,5] However, in practice, arbitrary position and force scaling capability is more useful and meaningful than transparency for dexterous teleoperation. In this article, the ideal response of teleoperation systems is defined as the position response x_m of master and the scaled position response of slave $k_p x_s$, and the force response f_m of master and the scaled force response $k_f f_s$ of slave by the operator's input f_{op} are identical, respectively, whatever the object dynamics are. This concept has already been proposed.[6,7]

However, it is very difficult to achieve the ideal response with real master/slave systems, because it is impossible to get an exact dynamic model of master/slave systems. Teleoperation systems are uncertain systems dynamically interacting with human/environment that may have time-varying impedances. If the local site and the remote site are combined with a communication channel, the two uncertain systems can again be considered to be coupled. In addition, communication time-delay is another significant problem.

There have been numerous efforts to obtain transparency for such complex coupled uncertain teleoperation systems with a fixed controller that has fixed gains. Lawrence indicated the conflicting issues between stability and transparency and proposed a unified four-channel control architecture that communicates the sensed forces and positions from the master to the slave, and vice versa.[2] Independently, Yokokohji also proposed a similar control architecture, which includes local force feedback.[5] Recently, it has been shown that the use of local force feedback at the master and the slave side enhances stability and performance in teleoperation systems.[3,8] Studies have shown that the fixed controller requires a four-channel architecture with local force feedback to achieve transparency. However, there have been limitations in producing robust performance for the uncertainties of the master/slave manipulators. Therefore, the design of fixed controllers for transparent teleoperation is still an open research problem.[9]

To cope with unknown environments and the uncertain parameters of the master/slave manipulators, several adaptive approaches have been proposed as alternatives. H-Zaad proposed an adaptive bilateral control scheme to obtain transparency in unknown or time-varying environments.[10] He used composite adaptive control schemes[11] and an impedance bilateral control architecture presented by Hannaford.[4] Lee presented an adaptive control scheme based on a position-force architecture to achieve stability and transparency for teleoperation in unknown or time-varying environments.[12] Zhu proposed an adaptive motion/force control-based approach to control bilateral teleoperation systems.[6] His method takes into account the full nonlinear dynamics of the master/slave manipulators. However, these approaches need to have environment or human impedance estimators that must converge fast enough for contact tasks.

In this article a novel adaptive bilateral control approach is proposed for obtaining the ideal response for uncertain teleoperation systems without the need of a fast converging estimator. The proposed bilateral controller estimates the dynamic parameters of the master/slave manipulator only, and the impedance of human/environment does not need to be estimated. The main contributions are to find a condition that is equivalent to getting the ideal response of teleoperation and to propose an adaptive scheme that makes the teleoperation system equal to the obtained equivalent condition. The obtained equivalent condition is a general set of methods by Lawrence,[2] Yokokohji[5], and Zaad.[8] The implicit common point of these methods, including the proposed one, is to achieve the similar closed-loop dynamics of master/slave manipulators. In other words, master and slave manipulators have a symmetric closed-loop dynamic structure. In fact, the goal of the teleoperation system is to synchronize the motion and force of the master and slave. Therefore, the similar closed-loop dynamics of the master/slave manipulator is a very useful property in providing high transparency performance. In addition, by making the closed-loop dynamics of the master/slave manipulator a similar form, the position/force tracking performance and the stability of the teleoperation system can be easily verified.

The remainder of this article is organized as follows. In Section 2, to provide an understanding of teleoperation structure, the dynamics of teleoperation systems are presented, and previous bilateral control approaches that give transparency with restricted conditions are analyzed. Then, in Section 3, a condition that is equivalent to getting the ideal response of teleoperation is obtained and analyzed. Section 4 explains the adaptive control scheme that makes the closed-loop dynamics of master and slave manipulators a similar form. In Section 5, the convergence property and stability of the proposed bilateral control scheme is proved. Section 6 demonstrates the experimental results. Finally, conclusions are summarized in Section 7.

2. PRELIMINARY

2.1. Dynamics

In this section the dynamics and parameters of teleoperation systems are explained to relate teleoperation control structure clearly. When a master/slave manipulator system interacts with a human/environment, the joint space dynamic equations of motion of the master arm and the slave arm are given by the equations

$$\text{Master:}\quad H_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + G_m(q_m) = \tau_m + J_m^T f_m \tag{1}$$

$$\text{Slave:}\quad H_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + G_s(q_s) = \tau_s - J_s^T f_s \tag{2}$$

where $q_m, q_s \in R^{n\times 1}$ are the joint angular positions, $H_m(q_m), H_s(q_s) \in R^{n\times n}$ are the symmetric positive-definite inertia matrices, $C_m(q_m,\dot{q}_m), C_s(q_s,\dot{q}_s) \in R^{n\times n}$ denote coriolis and centrifugal forces, and $G_m(q_m), G_s(q_s) \in R^{n\times 1}$ represent gravity forces of the master and the slave manipulator, respectively. $\tau_m, \tau_s \in R^{n\times 1}$ are the vector of applied joint torques, which are actually control inputs. $J_m, J_s \in R^{n\times n}$ are the Jacobian matrices of the master and slave manipulator. $f_m \in R^{n\times 1}$ denotes the force that the operator applies to the master manipulator, and $f_s \in R^{n\times 1}$ represent the forces that the slave arm applies to the object.

If the manipulator interacts with the environment, it is convenient to describe its dynamics in an operational space where manipulation tasks are naturally specified. The Cartesian space dynamic equations of motion can be represented as

$$(J_m^{-T}H_mJ_m^{-1})\ddot{x}_m + \left(J_m^{-T}C_mJ_m^{-1} + J_m^{-T}H_m\frac{d}{dt}(J_m^{-1})\right)\dot{x}_m + J_m^{-T}G_m = J_m^{-T}\tau_m + f_m \tag{3}$$

$$(J_s^{-T}H_sJ_s^{-1})\ddot{x}_s + \left(J_s^{-T}C_sJ_s^{-1} + J_s^{-T}H_s\frac{d}{dt}(J_s^{-1})\right)\dot{x}_s + J_s^{-T}G_s = J_s^{-T}\tau_s - f_s \tag{4}$$

where $x_m, x_s \in R^{n\times 1}$ is the displacement of the end-effectors of the master and slave manipulator, respectively.

The dynamics of the environment interacting with the slave arm is modeled by the linear system

$$f_s = M_e\ddot{x}_s + B_e\dot{x}_s + K_e x_s \tag{5}$$

where M_e, B_e, and K_e are $n\times n$ positive-definite matrices associated with inertia, viscous coefficient, and stiffness of the object, respectively. It is also assumed that the dynamics of the human operator can be approximately represented as a simple spring–damper–mass system,

$$f_{op} - f_m = M_{op}\ddot{x}_m + B_{op}\dot{x}_m + K_{op}x_m \tag{6}$$

where M_{op}, B_{op}, and K_{op} denote $n\times n$ mass, viscous coefficient, and stiffness of the operator, respectively, whereas f_{op} indicates force generated by the operator's muscles. It should be noted that the parameters of the human and environmental dynamics might change during the operation.

2.2. Previous Research

Among a number of bilateral control architectures introduced to provide ideal response, there have been a few schemes that have been successful in offering perfect transparency under ideal conditions.[2,5,8] To find a common point, these bilateral control schemes are analyzed in the frame of four-channel architecture with local force feedback as shown in Figure 1.

In 1993, a four-channel bilateral control architecture was proposed by Lawrence. Lawrence asserted that all four channels should be used to obtain transparency. By using all four channels, the master/slave closed-loop dynamics are composed as

$$(Z_m + C_m)(X_m - X_s) = F_m - F_s \tag{7}$$

$$(Z_s + C_s)(X_s - X_m) = F_m - F_s \tag{8}$$

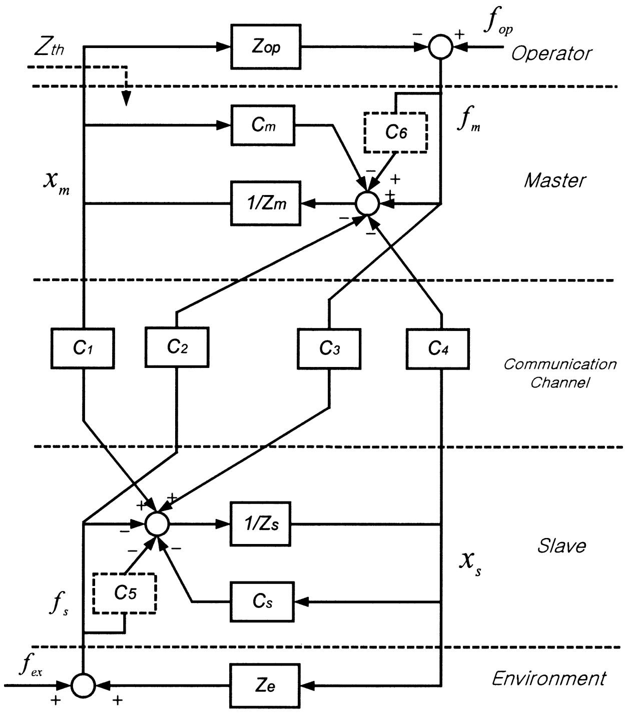

Figure 1. Block diagram of general four-channel bilateral control architecture. Local force feedback is added to the Lawrence's structure.

Here, Z_m and Z_s represent the linear dynamic models of the master and slave while C_m and C_s denote local position controllers of master and slave.

Independent of Lawrence, Yokokohji[5] has developed a general control architecture that is quite similar to that of Lawrence. If this control scheme is reorganized in the four-channel architecture with local force feedback, the constructed closed-loop dynamics are as follows:

$$m_m(s^2 + k_1 s + k_2)(X_m - X_s) = (1 + k_{mf})(F_m - F_s) \tag{9}$$

$$m_s(s^2 + k_1 s + k_2)(X_s - X_m) = (1 + k_{sf})(F_m - F_s) \tag{10}$$

Recently, H-Zaad obtained a high level of teleoperation performance by applying parallel position/force control architecture.[8] The closed-loop dynamics become as follows:

$$\left(m_m s^2 + k_{xvm} s + k_{xpm} + k_{xim}/s\right)(X_m - X_s) = k_{fpm}(F_m - F_s) \tag{11}$$

$$\left(m_s s^2 + k_{xvs} s + k_{xps}\right)(X_s - X_m) = (k_{fps} + k_{fis}/s)(F_m - F_s) \tag{12}$$

Note that the interesting point of these abovementioned bilateral control architectures is that even though these architectures have been developed in different ways, all of their closed-loop dynamics of the master/slave manipulator result in being similar as

$$-C_4(X_m - X_s) = C_2(F_m - F_s) \tag{13}$$

$$C_1(X_s - X_m) = C_3(F_m - F_s) \tag{14}$$

where $C_1, \ldots, C_4$ is the feedforward controller with rational transfer function in Figure 1.

3. SIMILAR CLOSED-LOOP DYNAMICS

In this section, we will derive an equivalent condition for the ideal response of teleoperation on the basis of the four-channel bilateral control architecture with local force feedback, depicted in Figure 1. Previously the ideal response was defined as the exact matching of the arbitrary scaled motion and force of master/slave manipulators.

From Figure 1, which is the general bilateral control architecture of one-DOF teleoperation systems, the closed-loop dynamics of master/slave manipulators are obtained as follows:

$$\text{Master:} \quad (Z_m + C_m)X_m + C_4 X_s = (C_6 + 1)F_m - C_2 F_s \tag{15}$$

$$\text{Slave:} \quad -C_1 X_m + (Z_s + C_s)X_s = C_3 F_m - (C_5 + 1)F_s \tag{16}$$

From the above general closed-loop dynamics, the ideal response is achieved if and only if the following four conditions are satisfied:

$$(Z_m + C_m)(Z_m + C_m) + C_4 C_1 = 0 \tag{17}$$

$$(C_6 + 1)(C_5 + 1) - C_2 C_3 = 0 \tag{18}$$

$$\frac{(Z_s + C_s)C_2 - (C_5 + 1)C_4}{(C_6 + 1)(Z_s + C_s) - C_4 C_3} = k_f \tag{19}$$

$$\frac{(Z_s + C_s)C_3 + (C_6 + 1)C_1}{(C_6 + 1)(Z_s + C_s) - C_4 C_3} = \frac{1}{k_p} \tag{20}$$

These conditions are obtained from the hybrid matrix.[4] Equations (17) and (18) mean the input impedance and the output admittance of the teleoperator should be zero. Equations (19) and (20) indicate force and position scaling. There can be numerous conditions that satisfy (17)–(20); however, one of the sufficient condition that is most realizable is as follows:

$$k_p C_1 = Z_s + C_s \tag{21}$$

$$C_2 = k_f(C_6 + I) \tag{22}$$

$$k_f C_3 = 1 + C_5 \tag{23}$$

$$C_4 = -k_p(Z_m + C_m) \tag{24}$$

The conditions (21)–(24) make the closed-loop dynamics of the master/slave manipulator similar, as follows:

$$\text{Master:} \quad -\frac{C_4}{k_p}(X_m - k_p X_s) = \frac{C_2}{k_f}(F_m - k_f F_s) \tag{25}$$

$$\text{Slave:} \quad C_1(k_p X_s - X_m) = C_3(F_m - k_f F_s) \tag{26}$$

The closed-loop dynamic equation of the master and the slave is expressed in terms of the position and force error. Each error dynamics is located at the either side of the closed-loop equations like (25) and (26). Note that all coefficients are positive except C_4. The closed-loop dynamics of the master and the slave have essentially identical forms. We call this closed-loop dynamic form of the master and the slave ''similar closed-loop dynamics'' (SCD).

The interesting point is that this form is the general expression of the closed-loop dynamics of Lawrence,[2] Yokokohji,[5] and H-Zaad,[8] mentioned in Section 2. In addition, the conditions (21)–(24) are equivalent to the perfect transparency condition of H-Zaad[3] when the position and force scaling factors are unity. Thus, we can conclude that the previous efforts to obtain the ideal response using fixed controllers are efforts to make the closed-loop dynamics of master/slave manipulators into SCD form. If the closed-loop dynamics of the master/slave manipulator are SCD, the teleoperation system can achieve ideal responses. However, fixed controllers have a limitation in constructing SCD when the dynamic parameters of the master/slave manipulator are uncertain and vary with time. Thus, in this article, an adaptive scheme is used to construct the SCD of master/slave manipulators.

4. ADAPTIVE APPROACH FOR CONSTRUCTING SCD

As mentioned previously, achieving the similar closed-loop dynamic structure is advantageous for obtaining transparency. In this section, an adaptive approach is introduced to construct the SCD of master/slave manipulators. The proposed adaptive bilateral control scheme is different from the previous ones[6,10,12] in that our adaptive scheme is based on the four-channel architecture without estimating environment parameters.

To construct similar closed-loop dynamics for the master and slave, we considered the parallel form symmetric control structure as

$$\tau_m = J_m^T\left(J_m^{-T}\Phi_{mr}\hat{\alpha}_m - K_m\varphi_m - f_m + K_{fm}(f_m - k_f f_s)\right) \tag{27}$$

$$\tau_s = J_s^T\left(J_s^{-T}\Phi_{sr}\hat{\alpha}_s - K_s\varphi_s + f_s + K_{fs}(f_m/k_f - f_s)\right) \tag{28}$$

where K_m, K_s, K_{fm}, and K_{fs} are the positive definite diagonal feedback gain matrices and k_f is a force scaling factor.

To analyze the convergence of the sliding function to the sliding surface, let the sliding function be

$$\varphi_m = \left(\dot{x}_m - k_p\dot{x}_s\right) + \lambda(x_m - k_p x_s) + K_I\int_0^t (x_m - k_p x_s)\,dt \tag{29}$$

$$\varphi_s = \left(\dot{x}_s - \dot{x}_m/k_p\right) + \lambda(x_s - x_m/k_p) + K_I\int_0^t (x_s - x_m/k_p)\,dt \tag{30}$$

where

$$\dot{x}_{mr} = k_p\dot{x}_s - \lambda(x_m - k_p x_s) - K_I\int_0^t (x_m - k_p x_s)\,dt$$

$$\dot{x}_{sr} = \dot{x}_m/k_p - \lambda(x_s - x_m/k_p) - K_I\int_0^t (x_s - x_m/k_p)\,dt$$

k_p is the position scaling factor, and $\lambda \in R^{n\times n}$ and $K_I \in R^{n\times n}$ are positive constant diagonal matrices which mean gains of error surface.

There exist vectors $\alpha_m \in R^{m\times 1}$, $\alpha_s \in R^{s\times 1}$ with components depending on the dynamics parameters of the master/slave manipulator, and regressor matrix[11] $\Phi_{mr} \in R^{n\times m}$, $\Phi_{sr} \in R^{n\times s}$ with components depending on the signals of the master/slave manipulator, such that

$$H_m \frac{d}{dt}\left(J_m^{-1}\dot{x}_{mr}\right) + C_m J_m^{-1}\dot{x}_{mr} + G_m = \Phi_{mr}\alpha_m \quad (31)$$

$$H_s \frac{d}{dt}\left(J_s^{-1}\dot{x}_{sr}\right) + C_s J_s^{-1}\dot{x}_{sr} + G_s = \Phi_{sr}\alpha_s \quad (32)$$

Based on the unified dynamic model (1) and (2), the update laws are

$$\dot{\hat{\alpha}}_m = -\Gamma_m(\Phi_{mr}^T J_m^{-1}\varphi_m + W_m^T J_m^{-1}E_{mw}) \quad (33)$$

$$\dot{\hat{\alpha}}_s = -\Gamma_s(\Phi_{sr}^T J_s^{-1}\varphi_s + W_s^T J_s^{-1}E_{sw}) \quad (34)$$

where W_m and W_s are the filtered version of Φ_m and Φ_s, the regressor matrix. As a result,

$$W_m(x_m, \dot{x}_m) = \frac{\lambda_p}{s+\lambda_p}\Phi_m(x_m, \dot{x}_m, \ddot{x}_m) \quad (35)$$

$$W_s(x_s, \dot{x}_s) = \frac{\lambda_p}{s+\lambda_p}\Phi_s(x_s, \dot{x}_s, \ddot{x}_s) \quad (36)$$

and E_{mw}, E_{sw} are the filtered prediction errors of filtered inputs τ_{mw}, τ_{sw}, f_{mw}, and f_{sw} as follows:

$$E_{mw} = J_m^{-T} W_m \hat{\alpha}_m - J_m^{-T}\tau_{mw} - f_{mw} \quad (37)$$

$$E_{sw} = J_s^{-T} W_s \hat{\alpha}_s - J_s^{-T}\tau_{sw} + f_{sw} \quad (38)$$

Γ_m and Γ_s are constant positive definite learning gain matrices.

5. STABILITY AND CONVERGENCE ANALYSIS

5.1. Convergence Analysis

By using the proposed adaptive bilateral controller, the closed-loop dynamics of the master/slave manipulator become similar as follows:

$$(J_m^{-T}H_m J_m^{-1})\dot{\varphi}_m + \left(J_m^{-T}C_m J_m^{-1} + J_m^{-T}H_m\frac{d}{dt}(J_m^{-1})\right)\varphi_m + J_m^{-T}\Phi_{mr}(\alpha_m - \hat{\alpha}_m) + K_m\varphi_m = K_{fm}(f_m - k_f f_s) \quad (39)$$

$$(J_s^{-T}H_s J_s^{-1})\dot{\varphi}_s + \left(J_s^{-T}C_s J_s^{-1} + J_s^{-T}H_s\frac{d}{dt}(J_s^{-1})\right)\varphi_s + J_s^{-T}\Phi_{sr}(\alpha_s - \hat{\alpha}_s) + K_s\varphi_s = K_{fs}(f_m/k_f - f_s) \quad (40)$$

These closed-loop dynamics of the master/slave manipulator are similar with $\varphi_s = -\varphi_m/k_p$. Subtracting (40) by multiplying $k_f K_{fm} K_{fs}^{-1}$ from (39) gives

$$\begin{aligned}(J_m^{-T}H_m J_m^{-1})\dot{\varphi}_m &+ \left(J_m^{-T}C_m J_m^{-1} + J_m^{-T}H_m\frac{d}{dt}(J_m^{-1})\right)\varphi_m \\ &+ J_m^{-T}\Phi_{mr}(\alpha_m - \hat{\alpha}_m) + K_m\varphi_m \\ &= -K_{fm}K_{fs}^{-1}\Bigg((J_s^{-T}H_s J_s^{-1})\dot{\varphi}_m \\ &\quad + \left(J_s^{-T}C_s J_s^{-1} + J_s^{-T}H_s\frac{d}{dt}(J_s^{-1})\right)\varphi_m \\ &\quad + k_p J_s^{-T}\Phi_{sr}(\alpha_s - \hat{\alpha}_s) + K_s\varphi_m\Bigg)\frac{k_f}{k_p}\end{aligned} \quad (41)$$

$$\begin{aligned}&\left[(J_m^{-T}H_m J_m^{-1}) + \frac{k_f}{k_p}K_{fm}K_{fs}^{-1}(J_s^{-T}H_s J_s^{-1})\right]\dot{\varphi}_m \\ &+ \Bigg[\left(J_m^{-T}C_m J_m^{-1} + J_m^{-T}H_m\frac{d}{dt}(J_m^{-1})\right) \\ &+ \frac{k_f}{k_p}K_{fm}K_{fs}^{-1}\left(J_s^{-T}C_s J_s^{-1} + J_s^{-T}H_s\frac{d}{dt}(J_s^{-1})\right)\Bigg]\varphi_m \\ &+ J_m^{-T}\Phi_{mr}(\alpha_m - \hat{\alpha}_m) \\ &+ k_f K_{fm}K_{fs}^{-1}J_s^{-T}\Phi_{sr}(\hat{\alpha}_s - \alpha_s) + K_m\varphi_m \\ &+ \frac{k_f}{k_p}K_{fm}K_{fs}^{-1}K_s\varphi_m = 0\end{aligned} \quad (42)$$

Consider the Lyapunov function candidate V defined by

$$\begin{aligned}V &= \frac{1}{2}(J_m^{-1}\varphi_m)^T H_m(J_m^{-1}\varphi_m) \\ &+ \frac{k_f}{k_p}\frac{1}{2}(J_s^{-1}\varphi_m)^T K_{fm}K_{fs}^{-1}H_s(J_s^{-1}\varphi_m) \\ &+ \frac{1}{2}\tilde{\alpha}_m^T\Gamma_m^{-1}\tilde{\alpha}_m + \frac{k_f k_p}{2}\tilde{\alpha}_s^T K_{fm}K_{fs}^{-1}\Gamma_s^{-1}\tilde{\alpha}_s\end{aligned} \quad (43)$$

where $\tilde{\alpha}_m = \hat{\alpha}_m - \alpha_m$ and $\tilde{\alpha}_s = \hat{\alpha}_s - \alpha_s$. Differentiating V along trajectories of (42) gives

$$\begin{aligned}\dot{V} &= \frac{1}{2}(J_m^{-1}\varphi_m)^T\left(\dot{H}_m - 2C_m\right)(J_m^{-1}\varphi_m)\\ &+ \frac{1}{2}\frac{k_f}{k_p}(J_s^{-1}\varphi_m)^T K_{fm}K_{fs}^{-1}\left(\dot{H}_s - 2C_s\right)(J_s^{-1}\varphi_m)\\ &+ \varphi_m^T\left(J_m^{-T}\Phi_{mr}\tilde{\alpha}_m - k_f K_{fm}K_{fs}^{-1}J_s^{-T}\Phi_{sr}\tilde{\alpha}_s\right.\\ &\left. - K_m\varphi_m - \frac{k_f}{k_p}K_{fm}K_{fs}^{-1}K_s\varphi_m\right)\\ &+ \dot{\tilde{\alpha}}_m^T\Gamma_m^{-1}\tilde{\alpha}_m + k_f k_p\dot{\tilde{\alpha}}_s^T K_{fm}K_{fs}^{-1}\Gamma_s^{-1}\tilde{\alpha}_s \end{aligned} \tag{44}$$

By using the skew-symmetric property of $(\dot{H}_m - 2C_m), (\dot{H}_s - 2C_s)$ and update lass (60), (61), differentiation of V results in

$$\begin{aligned}\dot{V} \leq &-\varphi_m^T K_m\varphi_m - \tilde{\alpha}_m^T W_m^T J_m^{-1}J_m^{-T}W_m\tilde{\alpha}_m\\ &- k_f k_p\varphi_s^T K_{fm}K_{fs}^{-1}K_s\varphi_s\\ &- k_f k_p\tilde{\alpha}_s^T W_s^T K_{fm}K_{fs}^{-1}J_s^{-1}J_s^{-T}W_s\tilde{\alpha}_s. \end{aligned} \tag{45}$$

And $\dot{V} = 0$ only when $\varphi_m, \tilde{\alpha}_m, \tilde{\alpha}_s = 0$. That means that V goes to zero until $V = 0$. Therefore, $\varphi_m, \tilde{\alpha}_m, \tilde{\alpha}_s \to 0$ as $t \to \infty$; that is, $(x_m - k_p x_s) \to 0$ as $t \to \infty$.

Since the position tracking and parameter estimation errors become zero, force tracking error also becomes zero from the similar closed-loop dynamics (39) and (40).

Due to the similar closed-loop structure of the master/slave manipulator, which is controlled by the proposed adaptive bilateral controller, position/force tracking is easily constructed.

5.2. Stability Analysis

For the stability analysis of a teleoperation system, the whole system including operator, master/slave manipulator, and environment is considered. Although the control scheme is developed for a multi-DOF case, stability only can be analyzed for one-DOF cases. From now on, capital letters are used to denote the Laplace transforms. For example, the similar closed-loop dynamics (39) and (40) can be represented as an impedance control structure as

$$\begin{aligned}&Z_{cm}(X_m - k_p X_s)\\ &\quad = k_{fm}(F_m - k_f F_s) + A_1 k_p X_s - A_2 X_m \end{aligned}\tag{46}$$

$$\begin{aligned}&Z_{cs}(X_s - X_m/k_p)\\ &\quad = k_{fs}(F_m/k_f - F_s) + B_1 X_m/k_p - B_2 X_s \end{aligned}\tag{47}$$

where

$$\begin{aligned} Z_{cm} &= m_m s^2 + (b_m + m_m\lambda + k_m)s\\ &\quad + (b_m\lambda + k_m\lambda) + k_m k_I/s\\ Z_{cs} &= m_s s^2 + (b_s + m_s\lambda + k_s)s\\ &\quad + (b_s\lambda + k_s\lambda) + k_m k_I/s\\ A_1 &= \tilde{\alpha}_{mm}(s+\lambda)s + \tilde{\alpha}_{mb}(s+\lambda)\\ A_2 &= \tilde{\alpha}_{mm}\lambda s + \tilde{\alpha}_{mb}\lambda\\ B_1 &= \tilde{\alpha}_{sm}(s+\lambda)s + \tilde{\alpha}_{sb}(s+\lambda)\\ B_2 &= \tilde{\alpha}_{sm}\lambda s + \tilde{\alpha}_{sb}\lambda \end{aligned}\tag{48}$$

In addition, environment and human dynamics can be expressed as

$$F_s = Z_e X_s \qquad F_m = F_{\text{op}} - Z_{\text{op}} X_m \tag{49}$$

where $Z_e = m_e s^2 + b_e s + k_e$, $Z_{\text{op}} = m_{\text{op}} s^2 + b_{\text{op}} s + k_{\text{op}}$.

Substituting (49) into the closed-loop dynamics (46) and (47), the closed-loop dynamics of the master/slave sides are given by

$$\begin{aligned}&(Z_{cm} + k_{fm}Z_{\text{op}} + A_2)X_m\\ &\quad + (k_{fm}k_f Z_e - Z_{cm}k_p - A_1 k_p)X_s = k_{fm}F_{\text{op}} \end{aligned}\tag{50}$$

$$\begin{aligned}&(k_{fs}Z_{\text{op}}/k_f - Z_{cs}/k_p - B_1/k_p)X_m\\ &\quad + (Z_{cs} + k_{fs}Z_e + B_2)X_s = k_{fs}F_{\text{op}}/k_f \end{aligned}\tag{51}$$

Substituting $E = X_m - k_p X_s$ into the master/slave manipulator closed-loop dynamics (50) and (51), the following results are obtained:

$$X_s = \frac{-(Z_{cm} + k_{fm}Z_{\text{op}} + A_2)E + k_{fm}F_{\text{op}}}{(k_{fm}k_f Z_e + k_{fm}k_p Z_{\text{op}} + k_p A_2 - k_p A_1)} \tag{52}$$

$$X_m = \frac{k_f(Z_{cs} + k_{fs}Z_e + B_2)E + k_{fs}k_p F_{\text{op}}}{(k_{fm}k_f Z_e + k_{fm}k_p Z_{\text{op}} + k_f B_2 - k_f B_1)} \tag{53}$$

Since all the coefficients of Z_e and Z_{op} are positive, stability depends on the coefficients of $A_2 - A_1$ and

$B_2 - B_1$. The coefficients are the parameter estimation errors as follows:

$$A_2 - A_1 = (m_m - \hat{m}_m)s^2 + \left(b_m - \hat{b}_m\right)s \quad (54)$$

$$B_2 - B_1 = (m_s - \hat{m}_s)s^2 + \left(b_s - \hat{b}_s\right)s \quad (55)$$

Thus, if the parameters are underestimated, that is, $m_m > \hat{m}_m$, $b_m > \hat{b}_m$, $m_s > \hat{m}_s$ and $b_s > \hat{b}_s$, the proposed controller is stable. The underestimated values give the intervening impedance effects[5] to the master/slave dynamics; thus the teleoperation system can preserve stability. However, there are stability margins that depend on the operator and environment impedance, even though the parameters are overestimated. The adaptive rules for which the stability is always guaranteed remain areas open to further study.

6. EXPERIMENTAL RESULTS

Figure 2 shows the teleoperation experimental setup used to verify the proposed control scheme. The experimental setup consists of a one-axis master handle and a one-axis slave link driven by Maxon BLDC motors EC118889 with 4000 pulse encoders. A planetary gearhead with a 23:1 ratio is used to increase the master and slave torques. Two strain gages are attached to the surface of each master and slave link which are composed of an aluminum bar of 2 mm $\times$ 15 mm $\times$ 140 mm to measure the operator and contact forces. The encoder signals and the amplified strain gage signals are transferred to a PC with a Pentium PRO-200 CPU board running the QNX real-time operating system, via encoder and 12-bit A/D board, respectively. Through the 12-bit D/A board mounted on the PC, torque commands are transferred to each servo controller of the motors.

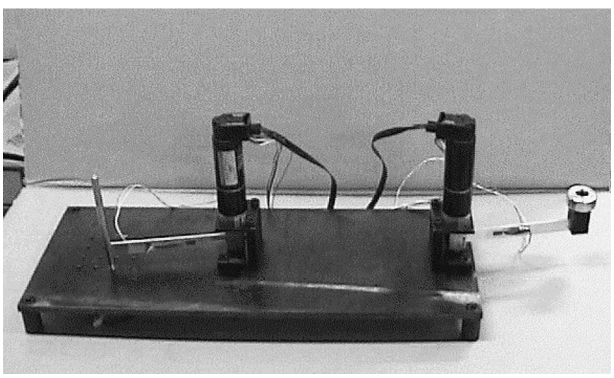

Figure 2. One-DOF master (right) and slave (left) manipulator for teleoperation. Strain gage bridge is attached to the arms to measure the interaction forces.

The control parameters are chosen as follows:

$$k_m = 0.005 \qquad k_s = 0.02 \qquad \lambda = 30 \qquad k_p = 60$$

$$\lambda_p = 100 \qquad k_{fm} = 1 \qquad k_{fs} = 0.6$$

$$\Gamma_m = \Gamma_s = \begin{bmatrix} 1e-10 & 0 \\ 0 & 0 \end{bmatrix}$$

The high sampling frequency of 1 kHz is used to calculate (27), (28), while the low sampling frequency of 100 Hz is used to calculate (33)–(38).

In the experiment, the operator pulls and pushes the master lever so that the slave makes three contacts with an environment of approximate stiffness 55,000 (N/m).

For the comparison, an experiment is performed with a non-SCD structure. The conventional adaptive bilateral controller is used to make the slave track the master command under any uncertain environments. In this adaptive scheme, the environment impedance is incorporated into the slave impedance, and the combined uncertainty parameters are estimated. This inclusion of the environment impedance removes the interaction force (F_s) in the closed loop dynamics of the slave. Thus, the SCD structure cannot be achieved anymore. For the master, the inertia and damping are canceled with estimated values, and force feedforward and position-PD control of the master is applied to transmit the slave force ideally. The controller gains are optimally tuned. Figure 3 illustrates the position and force tracking performance of the mentioned adaptive bilateral controller. There is a significant amount of error in position and force tracking in the contact regime. Since the impedance estimator in the adaptive controller is not fast enough, the transmitted force to the operator increases slowly compared to the actual contact force, and the slave cannot follow the master's command. Figure 4 shows the transmitted stiffness to the operator and the slave during the contact. The transmitted stiffness to the operator seems to be the filtered one of the slave. Thus, the operator feels filtered environment impedance.

In contrast, the proposed controller shows excellent position and force tracking performance, (Fig. 5). Position and force error is significantly reduced compared to that of the non-SCD structure, as shown in Fig. 3. Unlike the previous adaptive

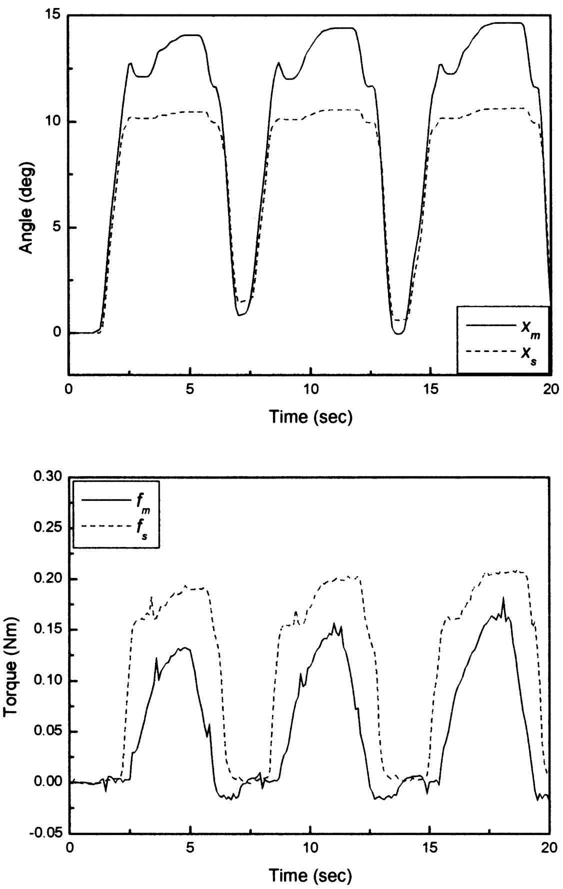

Figure 3. Experimental results: position and force tracking response with non-SCD control structure. System exhibits significant position and force error during the repeated contact and separation with an environment of approximate stiffness 55,000 (N/m).

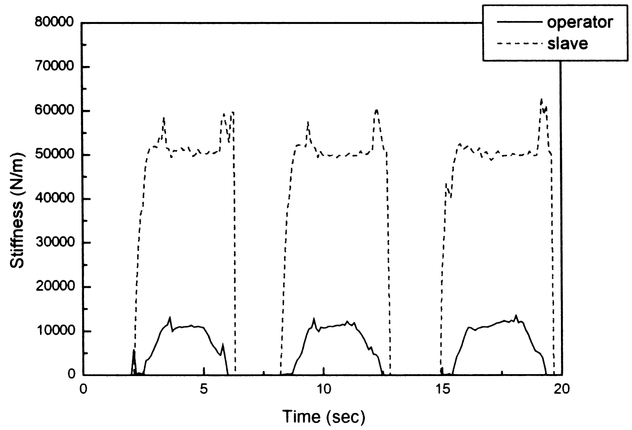

Figure 4. Comparison of the transmitted stiffness to the operator with the stiffness that the slave feels with the experimental results of Figure 3. The operator feels filtered environment impedance.

scheme, the proposed one increases the position/force tracking performance during the contact, since it has been designed to guarantee the ideal response without estimating the environment impedance. The transmitted force to the operator matches well with the actual contact force, and the slave follows the master with small error. The operator feels almost an equivalent stiffness to what the slave feels in Fig. 6. As a result, undistorted environment impedance is transmitted to the operator in the intermittent contact.

Figure 7 illustrates experimental results on position and force tracking with arbitrary scaling. Scaling parameters are $k_p = 2$ and $k_f = 1.5$. Independent of the scaling, the tracking results for both position and force are excellent. In this case, the operator feels the scaled down (1.5/2.0) environment impedance (Fig. 8).

In contrast to other adaptive approaches, the proposed control scheme does not use the human and environment impedances; instead, it just estimates the master and slave dynamic parameters to obtain ideal response by making the master and slave closed-loop dynamics similar. Therefore, the proposed control scheme can give ideal response to teleoperation systems, without efforts of estimating the human and environmental impedances.

7. CONCLUSIONS

A novel adaptive bilateral control scheme is proposed to obtain the ideal responses for uncertain teleoperation systems. The proposed bilateral controller uses similar closed-loop dynamic characteristics, which are the structural properties that the successful bilateral controllers had in common. The adaptive approach is used to achieve the similar closed-loop dynamics for master and slave manipulators with uncertainties. Since the proposed bilateral controller does not estimate the human and environment parameters, but just estimates the master and slave dynamic parameters only, the difficulties encountered in developing environment impedance estimators that converge fast enough for contact tasks are removed. Due to the similarity, the convergence and stability properties of the position and force are proved easily. Through the experiment, the performance of the proposed bilateral control scheme is demonstrated. Although the sta-

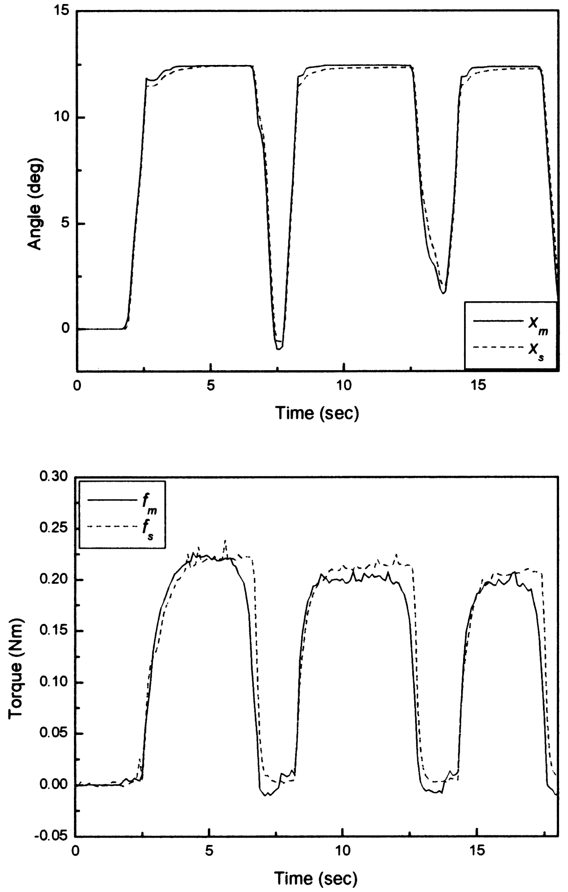

Figure 5. Experimental results: position and force tracking response with the proposed SCD control structure. Position and force tracking performance is increased with the same task as in Figure 3.

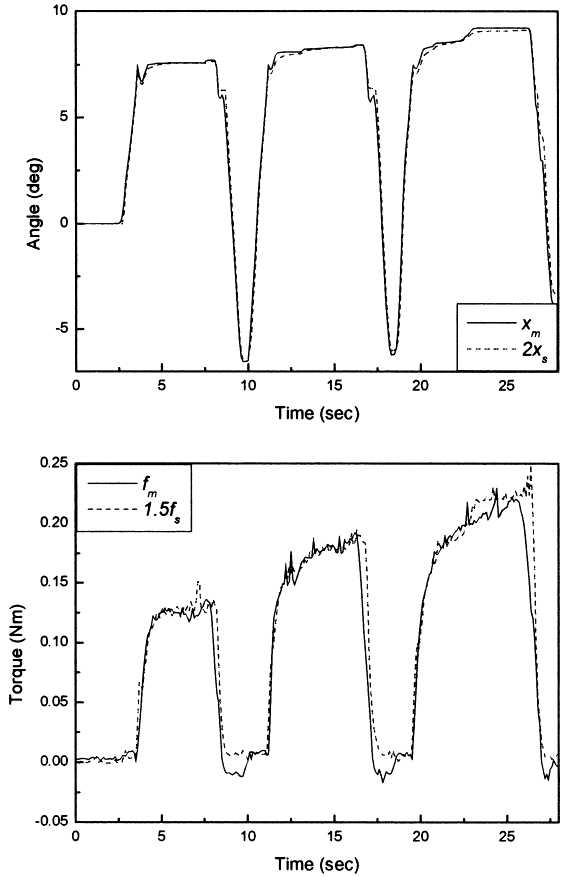

Figure 7. Experimental results: scaled teleoperation with the proposed controller. Transmitted position to the slave is scaled down 0.5 times, and transmitted force to the master is magnified 1.5 times. Position and force tracking performance is also excellent with the same tack as in Figure 5.

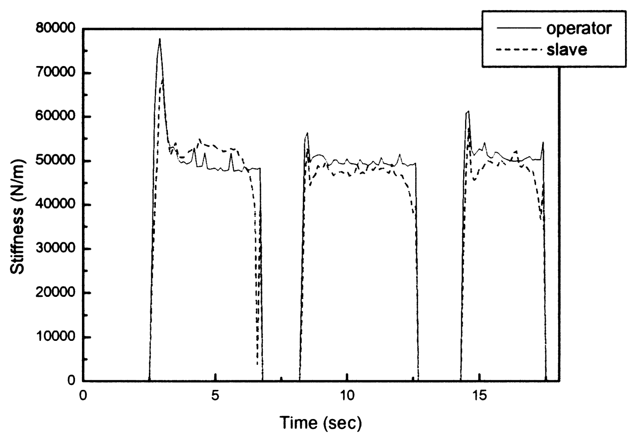

Figure 6. Comparison of the transmitted stiffness to the operator with the stiffness that the slave feels with the experimental results of Figure 5. The operator feels an almost equivalent impedance to what the slave feels.

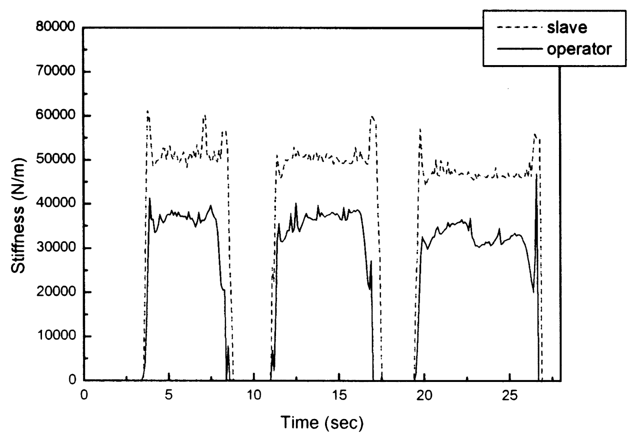

Figure 8. Comparison of the transmitted stiffness to the operator with the stiffness that the slave feels with the experimental results of Figure 7. The operator feels scaled down (1.5/2.0) impedance to what the slave feels.

bility can be proved only for a one-DOF case, the proposed control scheme can guarantee ideal response for fully nonlinear dynamics of master/slave manipulators.

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