A Novel Adaptive Bilateral Control Scheme using Dual Closed-loop Dynamic Characteristics of Master/Slave Manipulators

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Abstract

This paper presents a novel adaptive bilateral control scheme for obtaining transparency for teleoperation systems that has uncertainties. It has been found that a condition that is equivalent to getting an ideal response in teleoperation is to make the closed-loop dynamics of master and slave manipulators dual. An adaptive approach is applied to achieve the duality for the uncertain master and slave manipulators. Due to the dual closed-loop dynamic characteristics of master/slave teleoperation systems, excellent position and force tracking performance can be obtained without concerning the impedance variation of human and environment. The validity of the theoretical results is verified by experiments with a 1-DOF master/slave system.

1. Introduction

Teleoperation systems have been extensively studied since the pioneering work of Goertz [1], motivated by a large variety of applications, ranging from nuclear operation and space explorations to underwater tasks and medical applications. Teleoperation enables an operator to manipulate dangerous, remote or delicate tasks via a master/slave manipulator with better safety, at lower cost, and even with better accuracy [9]. Recently, application areas are extended to an entertainment and a training field with virtual reality.

The objective of a teleoperation system is to make the slave exactly reproduces the master’s motions and the master accurately transmits the measured slave force. This is the ideal response of the teleoperation system.

However, it is very difficult to achieve the ideal response with real master/slave systems, because it is impossible to get the exact dynamic model of master/slave systems, in teleoperation systems, uncertain master/slave systems dynamically interacting with human/environment, which may have time-varying impedance. If the local and remote site is combined with communication channel, the uncertain two systems are coupled, again. Also, communication time-delay is another big problem.

There have been numerous efforts to obtain the ideal response for such complex coupled uncertain teleoperation systems with 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 [6]. Independently, Yokokohji also proposed similar control architecture, which includes local force feedback [11]. Recently, it has been shown that the use of local force feedback at the master and slave side enhances stability and performance in teleoperation systems [4,5]. Studies have shown that fixed controller require a four-channel architecture with local force feedback to achieve transparency. However, there has been limitation to produce robust, satisfactory performance for the uncertainties of the master/slave manipulators. Therefore, the design of the fixed transparent controllers is still an open research problem [8].

To cope with unknown environment and the uncertain parameters of the master/slave manipulators, several adaptive approaches have been proposed as an alternative approach. H-Zaad proposed an adaptive bilateral control scheme to obtain transparency in unknown or time-varying environments [3]. He used composite adaptive control schemes [10] and an impedance bilateral control architecture presented by Hannaford [2] is used. Lee presented an adaptive control scheme based on position-force architecture to achieve the stability and transparency for teleoperation in unknown or time-varying environments [7]. Zhu proposed an adaptive motion/force control based approach to control the bilateral teleoperation systems [12]. It takes into account the full nonlinear dynamics of the master/slave manipulators. However, these approaches need to have environment or human impedance estimators that
converge fast enough for contact tasks.

A novel adaptive bilateral control approach is proposed to get the ideal response for uncertain teleoperation systems avoiding the difficulties of the fast converging estimator. The proposed bilateral controller estimates the dynamic parameters of the master/slave manipulator and the human/environment estimator is not involved in the control scheme. A condition has been found that is equivalent to getting an ideal response of teleoperation and an adaptive scheme has been proposed to make the teleoperation system equal to the obtained equivalent condition. The obtained equivalent condition is a general set of Lawrence [6], Yokokohji [11] and Zaad [5]. The implicit common point of these, including the proposed one, is dual closed-loop dynamics of master/slave manipulators. In other words, master and slave manipulators have symmetric closed-loop dynamics of master/slave manipulators. In fact, the goal of the teleoperation system is to make the master/slave follow the motion and force, each other. Therefore, the dual closed-loop dynamics of the master/slave manipulator are very useful property to provide high transparency performance. By making the closed-loop dynamics of the master/slave manipulator dual, the position/force tracking performance and the stability of the teleoperation system can be proved with ease. Although the development is not shown in this paper, this approach can be extended to the multi-DOF cases with ease.

2. Preliminary

2.1. Dynamics

In this part, the dynamics and parameters of teleoperation systems are explained to extend teleoperation control structure clearly. Most master/slave systems consist of arms with multiple DOF. However, a one DOF system is considered in order to make the equation derivation more intuitive.

The dynamics of the master arm and slave arm is given by the following equations:

\[ \text{Master: } m_x \ddot{x}_x + b_x \dot{x}_x = u_x + f_u \]  
\[ \text{Slave: } m_x \ddot{x}_s + b_x \dot{x}_s = u_x - f_x \]  

where \( x_x \) and \( x_s \) denote the displacement of the master and slave arm, \( m_x \) and \( b_x \) represent mass and viscous coefficient of the master arm respectively, whereas \( m_s \) and \( b_s \) are those of the slave arm. In addition, \( f_u \) denotes the force that the operator applies to the master arm, and \( f_x \) denotes the forces that the slave arm applies to the environment. Actuator driving forces of master and salve arms are represented by \( u_x \) and \( u_s \), respectively.

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

\[ f_e = m_s \ddot{x}_s + b_s \dot{x}_s + k_s x_s \]  

where \( m_s \), \( b_s \) and \( k_s \) denote mass, viscous coefficient and stiffness of the object, respectively.

It is also assumed that the dynamics of the operator can be approximately represented as a simple spring-damper-mass system:

\[ f_o - f_s = m_o \ddot{x}_o + b_o \dot{x}_o + k_o x_o \]  

where \( m_o \), \( b_o \) and \( k_o \) denote mass, viscous coefficient and stiffness of the operator, respectively, whereas \( f_o \) means the force generated by the operator’s muscles. It should be noted that the parameters of the operator arm dynamics might change during the operation.

2.2. Previous Researches

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 [5, 6, 11]. To find a common point, these bilateral control schemes are analyzed in the frame of four-channel architecture with local force feedback, which is depicted in Figure 1.

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

\[ (Z_x + C_o)(X_x - X_s) = F_m - F_o \]
\[ (Z_x + C_o)(X_s - X_x) = F_o - F_m \]

Independent of Lawrence, Yokokohji [11] have 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:

\[ m_x \left( s^2 + k_x s + k_e \right)(X_x - X_s) = \left( I + k_x \right)(F_m - F_o) \]
\[ m_s \left( s^2 + k_x s + k_e \right)(X_s - X_x) = \left( I + k_x \right)(F_o - F_m) \]

In recent, H-Zaad obtained good teleoperation performance by applying parallel position/force control architecture [5]. The closed-loop dynamics become as follows:

\[ m_o s^2 + k_o s + k_o \left( X_s - X_e \right) = k_o \left( F_o - F_e \right) \]
\( (m_s \dot{x}_s + k_m \dot{x}_s + k_m x_s)(X_s - X_s) = (k_m + k_m / s)(F_m - F_s) \)

Note that the interesting point of these mentioned bilateral control architectures is that all of their closed-loop dynamics of the master/slave manipulator are resulted to be dual, even though these architectures have been developed in different ways. Also, these all architectures meet the perfect transparency condition in [4].

3. Dual Closed-loop Dynamics (DCD)

In Section 2, it is found that the previous efforts to obtain the ideal response using fixed controllers are efforts to make the closed-loop dynamics of the master/slave manipulator into dual form as follows:

\[
-C_s(X_s - X_s) = C_s(F_s - F_s) \quad (5)
\]

\[
C_s(X_s - X_s) = C_s(F_s - F_s) \quad (6)
\]

where \( C_s, \cdots, C_s \) are feed-forward controller of Figure 1 with rational transfer function. If the closed-loop dynamics of the master/slave manipulator are dual, it is equivalent to that the teleoperation system can achieve the ideal response. However, fixed controllers have a limitation to construct DCD, when the dynamic parameters of the master/slave manipulator are uncertain and vary with time. Thus, in this paper, adaptive scheme is used to construct DCD of the uncertain and time-varying master/slave manipulator.

4. Adaptive Approach to Construct DCD

As mentioned previously, maintaining the dual closed-loop dynamic structure is advantageous to obtain transparency. In this section, an adaptive approach is introduced to construct DCD of the master/slave manipulator. The proposed adaptive bilateral control scheme is different from the previous ones [3, 7, 12]. This adaptive scheme is based on the four-channel architecture without estimating environment parameters.

To construct dual closed-loop dynamics about master and slave, we considered the parallel form symmetric control structure as follows:

\[
u_m = \Phi_{\alpha_m} \alpha_m - k_m \varphi_m - f_m + k_m (f_m - f_s)
\]

\[
u_s = \Phi_{\alpha_s} \alpha_s + k_\varphi \varphi_s + f_s + k_\varphi (f_s - f_m)
\]

where \( k_m, k_s, \varphi_m \) and \( k_s, \alpha_m \) is the positive definite feedback gain. There exist vector \( \alpha_m, \alpha_s \) with components depending on the dynamics parameters of master/slave manipulator, and regressor matrix [10] \( \Phi_\alpha \), \( \Phi_\varphi \) with components depending on the signals of the master/slave manipulator, such that

\[
\alpha_m = \begin{bmatrix} m_s & b_s \end{bmatrix}, \quad \alpha_s = \begin{bmatrix} m_s & b_s \end{bmatrix}
\]

\[
\varphi_m = \begin{bmatrix} \varphi_m \\ \varphi_m \end{bmatrix}, \quad \varphi_s = \begin{bmatrix} \varphi_s \\ \varphi_s \end{bmatrix}
\]

\[\varphi_m \text{ and } \varphi_s \text{ is the sliding function. To analyze the convergence of the sliding function to the sliding surface, let the sliding function be}
\]

\[
\varphi_m = (\dot{x}_m - \dot{\hat{x}}_m) + \lambda (x_m - \dot{x}_m) + k_s (x_m - \dot{x}_m) \int (x_m - \dot{x}_m) \text{d}t
\]

\[
\varphi_s = (\dot{x}_s - \dot{\hat{x}}_s) + \lambda (x_s - \dot{x}_s) + k_s (x_s - \dot{x}_s) \int (x_s - \dot{x}_s) \text{d}t,
\]

\[
\lambda \text{ and } k_s \text{ are positive scalars.}
\]

Based on the unified dynamic model (1) and (2), the update laws is given below,

\[
\dot{\alpha}_m = -F_m \Phi_{\alpha_m} \varphi_m + W_m \dot{E}_m
\]

\[
\dot{\alpha}_s = -F_s \Phi_{\alpha_s} \varphi_s + W_s \dot{E}_s
\]

where, \( W_m \) and \( W_s \) is the filtered version of \( \Phi_{\alpha_m, \alpha_s} \), the regressor matrix. As a result,

\[
W_m(x_m, \dot{x}_m) = \frac{\lambda_m}{s + \lambda_m} \Phi_{\alpha_m} (x_m, \dot{x}_m)
\]

\[
W_s(x_s, \dot{x}_s) = \frac{\lambda_s}{s + \lambda_s} \Phi_{\alpha_s} (x_s, \dot{x}_s)
\]

and \( E_m, E_s \) is the filtered prediction error of filtered input \( u_m, u_s, f_m, f_s \) as follows:

\[
E_m = W_m \dot{\alpha}_m - u_m - f_m,
\]

\[
E_s = W_s \dot{\alpha}_s - u_s + f_s
\]

\( \Gamma_m \) and \( \Gamma_s \) are constant positive definite learning gain matrices.

We also assume that the scales of position and force are identical between the master and slave sites. Practically speaking, however, we may face the situations where the scales are different between the operator and the remote object. It is possible to deal with such situations by introducing the scaling coefficients of position and force in (7) and (8). In this Section, however, we will consider the case when both scales are unity to simplify the discussion.

5. Stability and Convergence Analysis

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

\[ m_\alpha \ddot{\alpha}_\alpha + (b_\alpha + k_\alpha) \dot{\alpha}_\alpha + k_\alpha (\alpha_{\text{des}} - \tilde{\alpha}_\alpha) = k_\alpha (f_\alpha - f) \] (17)

\[ m_\beta \ddot{\beta}_\alpha + (b_\beta + k_\beta) \dot{\beta}_\alpha + k_\beta (\alpha_{\text{des}} - \tilde{\alpha}_\alpha) = k_\beta (f_\beta - f) \] (18)

After subtracting both sides of (18) by multiplying \( k_\alpha / k_\beta \) from (17), we obtain the position tracking capability and parameter convergence property using quadratic Lyapunov function candidate as follows:

\[ V = \frac{1}{2} \left( m_\alpha \dot{\alpha}_\alpha + \frac{k_\alpha}{k_\beta} m_\beta \dot{\beta}_\alpha \right) \dot{\alpha}_\alpha + \frac{f}{2} \alpha_{\text{des}}^T \alpha_{\text{des}} + \frac{k_\alpha}{k_\beta} \alpha_{\text{des}}^T \alpha_{\text{des}} \] (19)

where \( \tilde{\alpha}_\alpha = (\tilde{\alpha}_\alpha - \alpha_{\text{des}}) \) and \( \tilde{\alpha}_\beta = (\tilde{\alpha}_\beta - \alpha_{\text{des}}) \).

Differentiating \( V \) gives a result that

\[ \dot{V} \leq \left( k_\alpha + b_\alpha \right) \dot{\alpha}_\alpha - \frac{k_\alpha}{k_\beta} \left( k_\beta + b_\beta \right) \dot{\beta}_\alpha - \tilde{\alpha}_\alpha \dot{\alpha}_\alpha W_\alpha \tilde{\alpha}_\alpha - \frac{k_\alpha}{k_\beta} \tilde{\alpha}_\beta \dot{\beta}_\beta W_\beta \tilde{\beta}_\beta \] (20)

Therefore, position tracking and parameter estimation errors become zero as \( t \to \infty \). Once the position and parameter estimation errors converge, force tracking error also becomes zero from the dual closed-loop dynamics (17) and (18).

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

For the stability analysis of a teleoperation system, whole system including operator, master/slave manipulator and environment is considered.

From now on, the capital letters are used to denote the Laplace transforms. For example, the dual closed-loop dynamics (17) and (18) can be represented as impedance control structure as follows:

\[ Z_\alpha \left( X_{\alpha} - X_\alpha \right) = k_\alpha \left( F_\alpha - F \right) + A_\alpha X_\alpha - A_\alpha X_\alpha \] (21)

\[ Z_\beta \left( X_{\beta} - X_\beta \right) = k_\beta \left( F_\beta - F \right) + B_\alpha X_\beta - B_\beta X_\beta \] (22)

where each coefficient is represented by the control variables. Also, environment and human dynamics can be expressed as follows:

\[ F_\alpha = Z_\alpha X_\alpha, \quad F_\beta = Z_\beta X_\beta \] (23)

where \( Z_\alpha = m_\alpha s^2 + b_\alpha s + k_\alpha, \quad Z_\beta = m_\alpha s^2 + b_\alpha s + k_\alpha \).

Substituting (23) into the closed-loop dynamics (21) and (22), the closed-loop dynamics of the master/slave sides are given by

\[ \left( Z_\alpha + k_\alpha \right) X_\alpha + \left( k_\alpha Z_\alpha - A_\alpha \right) X_\alpha = k_\alpha F_\alpha \] (24)

\[ \left( k_\beta Z_\beta - Z_\beta - B_\beta \right) X_\beta + \left( Z_\beta + k_\beta Z_\beta + B_\beta \right) X_\beta = k_\beta F_\beta \] (25)

Substituting \( E = X_{\alpha} - X_\alpha \) into the master/slave manipulator closed-loop dynamics (24) and (25), the following results are obtained:

\[ X_\alpha = \frac{-Z_\alpha + k_\alpha Z_\alpha + A_\alpha E + k_\alpha F_\alpha}{k_\alpha Z_\alpha + k_\alpha Z_\alpha + A_\alpha + A_\alpha} \] (26)

\[ X_\beta = \frac{Z_\beta + k_\beta Z_\beta + B_\beta E + k_\beta F_\beta}{k_\beta Z_\beta + k_\beta Z_\beta + B_\beta + B_\beta} \] (27)

Since all the coefficients of \( Z_\alpha \) and \( Z_\beta \) are positive, the stability depends on the coefficients of \( A_\alpha - A_\alpha \) and \( B_\beta - B_\beta \). The coefficients are the parameter estimation errors as follows:

\[ A_\alpha - A_\alpha = \left( m_\alpha - \tilde{m}_\alpha \right) s^2 + \left( b_\alpha - b_\alpha \right) s \] (28)

\[ B_\beta - B_\beta = \left( m_\alpha - \tilde{m}_\alpha \right) s^2 + \left( b_\alpha - b_\alpha \right) s \] (29)

Thus, if the parameters are underestimated that is, \( m_\alpha > \tilde{m}_\alpha, \quad b_\alpha > \tilde{b}_\alpha, \quad m_\alpha > \tilde{m}_\alpha, \quad b_\alpha > \tilde{b}_\alpha \), the proposed controller is stable. The underestimated values give the intervening impedance effects [11] to the master/slave dynamics, thus the teleoperation system can preserve stability. However, there are stability margins that are depending on the operator and environment impedance, even though the parameters are over estimated. The adaptive rules that the stability is always guaranteed are remains as further works.

6. Experimental Results

Figure 2 shows the teleoperation experimental setup 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 4,000 pulse encoders. A planetary gearhead with 23:1 ratio is used to increase the master and slave torques. Two strain gages to measure the operator and contact forces, are attached to the surface of each master and slave link which is composed of an aluminum bar of 2mm×15mm×140mm. The encoder signals and the amplified strain gage signals are transferred to a PC with 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.

The control parameters are chosen as follows:

\[ k_\alpha = 0.005, \quad k_\beta = 0.02, \quad \lambda = 30, \quad k_\alpha = 60, \quad \lambda = 100 \]
\[ k_u = 1, \quad k_p = 0.6 \quad \Gamma_u = \Gamma_p = \begin{bmatrix} 1e-10 & 0 \\ 0 & 0 \end{bmatrix}. \]

The high sampling frequency of 1kHz is used to calculate (7), (8), while the low sampling frequency of 100Hz is used to calculate (13)-(16).

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

First, an experiment is performed with non-DCD structure. The conventional adaptive bilateral controller with the position-PD control of the master is applied. Due to the presence of the parameter estimation problem and uncertainties, it is impossible to construct DCD (the equivalent condition to getting the ideal response) with this controller. 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. The slave cannot track the master position commands, and the operator feel the smaller stiffness than the actual one.

On the other hand, the proposed controller shows the excellent position and force tracking performance, in Figure 4. The position and force error is significantly reduced compared to that of Figure 3.

In contrast to the other adaptive approaches, the proposed control scheme does not use the human and environment impedances but just estimate the master and slave dynamic parameters to obtain the ideal response by making the master and slave closed-loop dynamics dual. Therefore, the proposed control scheme can give the ideal response to teleoperation systems, independent of the variation of human and environment 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 dual closed-loop dynamic characteristics, which are the characteristics that the successful bilateral controllers had in common. The adaptive approach is used to maintain the dual closed-loop dynamics for the uncertain master and slave manipulators. Since the proposed bilateral controller does not estimate the human and environment parameters and just estimate 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 duality, the convergence and stability property of the position and force is proved easily. Through the experiment, the performance of the proposed bilateral control scheme is demonstrated. The proposed scheme can be easily extended to the multi-DOF case.

References


Figure 1. General four-channel bilateral control architecture with local force feedback

Figure 2. Picture of the 1-DOF experimental setup

Figure 3. Position/force tracking response with non-DCD control structure

Figure 4. Position/force tracking response with the proposed controller (DCD control structure)