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Research Article

Sensor-less force-reflecting macro–micro telemanipulation systems by piezoelectric actuators

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ABSTRACT

This paper establishes a novel control strategy for a nonlinear bilateral macro–micro teleoperation system with time delay. Besides position and velocity signals, force signals are additionally utilized in the control scheme. This modification significantly improves the poor transparency during contact with the environment. To eliminate external force measurement, a force estimation algorithm is proposed for the master and slave robots. The closed loop stability of the nonlinear micro–micro teleoperation system with the proposed control scheme is investigated employing the Lyapunov theory. Consequently, the experimental results verify the efficiency of the new control scheme in free motion and during collision between the slave robot and the environment of slave robot with environment, and the efficiency of the force estimation algorithm.

1. Introduction

In bilateral teleoperation, the master and slave robots interact with each other via communication channels. Examples of such applications are space technology, underwater exploration, telesurgery, telepresence, and handling toxic and harmful materials [1,2]. A new function is in the area of macro–micro teleoperation, where, operators are restricted in manipulating micro objects directly. Therefore, a macro–micro teleoperation system can enable the manipulation of tasks on a micro scale. Smart actuators such as piezoelectric stages are widely used as slave manipulators in macro–micro manipulation applications [3].

In bilateral teleoperation, stability and transparency of the closed loop system are two primary goals which diverse control approaches have been proposed to reach them. Transparency means the operator feels as if he is manipulating the remote object directly. Thus, it can be said that transparency is attained when the slave robot follows the master robot's position and if the slave robot comes in contact with the environment; the operator on the master side can sense the reflected environmental force. It is evident that achieving these goals generally improves the operator's ability to perform complex tasks.

The most conventional control schemes for nonlinear systems, i.e. Proportional Derivative (PD) controllers, normally use position and velocity signals from the master and slave robots [4–9]. In these control approaches, stability and force reflection are attained, but position error occurs during collision of the slave robot with the environment. This problem disrupts closed-loop system transparency during contact motions.

Transparency is higher, if the force signals are transmitted in conjunction with the position and velocity signals; as a result the operator has a better sense of the environment. Thus, some control schemes have been designed to enhance system transparency by using measured force signals in the control structure [10–15]. In such cases, bilateral teleoperation system stability is considered, but it is only applicable to linear bilateral teleoperation systems. It is worth noting that the most prevalent dynamic model for many robotic tasks is nonlinear. Moreover, force measurement of the operator and environment may not always be possible and affordable. This concern is greater in micromanipulation processes.

To overcome these drawbacks, several works have been done in the case of robotic manipulators to estimate external forces [16–20]. In these researches external force exerted on the robotic manipulators was estimated and imported into the control scheme; however, for some major reasons the employed algorithms are not applicable for teleoperation systems. In robotic manipulators, external force was estimated based on the mentioned algorithms, then it was employed on the control scheme, and subsequently, system stability was taken

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into account with the proposed controller. In contrast with robotic manipulators, teleoperation systems include three sections: master robot, slave robot and communication channels. All three sections affect system stability, therefore the effects must be considered in control scheme design to achieve proper stability and transparency in closed-loop systems. Thus, due to this significant difference between robotic manipulators and teleoperation systems, it is not possible to apply every force estimation algorithm or control scheme for teleoperation systems. For example, time delay is an undesirable problem associated only with communication channels in teleoperation systems. This issue can deteriorate system stability and transparency, therefore it must be considered in control scheme and force estimation algorithm to attain appropriate performance.

Several researchers have proposed force estimation algorithms to eliminate force signal measurement in teleoperation systems [21–25]. External force estimation on the master and slave sides combined with a modified version of sliding-mode bilateral teleoperation has been considered [21,22]. In these studies, force reflection was not taken into account, although it is one of the most important functions in a closed-loop system. A synchronization bilateral teleoperation scheme using a state observer to estimate external forces has also been suggested [23]. However, force synchronization has not yet been achieved.

Another problem concerning the mentioned force estimation algorithms is that employing them does not theoretically guarantee closed-loop system stability.

In [24], stability and transparency analyses for the overall closed-loop system were presented. However, this scheme is appropriate only for linear systems. In [25], external force was experimentally estimated but it was not demonstrated analytically. The other drawback is that transparency was not considered in the control system. In [26,27], force estimation algorithm was proposed based on the improved extended active observer (IEAOB) and extended active observer (EAOB) for teleoperation systems, respectively. In these researches, it was demonstrated that system stability was satisfied in the presence of external uncertainties, but system transparency was not taken into account.

In the present study, a new control scheme is proposed using force signals to control a nonlinear bilateral macro–micro teleoperation system with communication channel time delay. A modified force estimation algorithm is proposed to eliminate force measurement. The stability and transparency of the bilateral teleoperation system is investigated in the presence of estimated external forces and time delay between communication channels. The Lyapunov criterion is utilized for stability analysis. It is demonstrated theoretically that the system is stable, the force estimation error converges to zero and system transparency is enhanced to a great extent in the presence of time delay.

Consequently, experimental results validate the precise estimation of external forces. The proposed controller achieves position tracking in free motion and force reflection when the slave robot is in contact with the environment. It is obvious that transparency is remarkably superior to conventional control schemes without force signals.

2. Model definition

A dynamic model of a macro–micro teleoperation system is considered as follows:

$$M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + g_m(q_m) = T_m - F_h \tag{1}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + g_s(q_s) = F_e - T_s \tag{2}$$

where $\ddot{q}_m, \dot{q}_m, q_m, \ddot{q}_s, \dot{q}_s, q_s \in R^n$ are acceleration, velocity and joint position of the master and slave robots; $F_h, F_e \in R^n$ are the operator and environmental forces, respectively, and $T_m, T_s \in R^n$ represent the control inputs; $M_m(q_m), M_s(q_s) \in R^{n\times n}$ are symmetric and positive-definite inertia matrices; $C_m(q_m,\dot{q}_m), C_s(q_s,\dot{q}_s) \in R^{n\times n}$ represent the Coriolis matrices of the master and slave systems; and $g_m(q_m), g_s(q_s) \in R^n$are the vectors of the master and slave gravitational forces, respectively.

The dynamic model of robotic manipulators with rotational joints has the following properties:

P1: $\dot{M}_i(q_i) = C_i(q_i,\dot{q}_i) + C_i^T(q_i,\dot{q}_i)$.
P2: $\exists \alpha_i, \beta_i \in R > 0$ such that $\beta_i I \le M_i(q_i) \le \alpha_i I$.
P3: For all $q_i, x, y \in R^n$, $\exists k_{ci} \in R > 0$ such that $|C_i(q_i,x)y| \le k_{ci}|x||y|$, where $|.|$ is the Euclidean norm.

Time delays in communication channels are always present in teleoperation systems. The time delay is considered constant and equal in forward and backward channels $(T \ge 0)$.

It is assumed that the operator and environment are passive. Operator and environment passivity has been adopted in previous studies [4,6]. Therefore,$k_\mathrm{i} \in \mathrm{R} \ge 0$ such that

$$\begin{aligned} &\int_0^t k_p^2 \dot{q}_m^T(a)(1-\theta)F_h(a)da \ge -k_m \\ &\int_0^t -\dot{q}_s^T(a)(1-\theta)F_e(a)da \ge -k_s \end{aligned} \tag{3}$$

for all$t \ge 0$, k_p is the position scale factor andθ is the coefficient of estimated force that can vary from zero to one.

3. Nonlinear bilateral macro–micro teleoperation control design

The control input designed for the macro–micro bilateral teleoperation system consists of position error between the master and slave robots, velocity signals along with estimated operator and environmental forces. Nonetheless, two main uncertainties remain:

(1) The scale difference between the master and slave robots.
(2) Lack of real operator and environmental forces.

The proposed control scheme with a suitable coefficient as well as estimated operator and environmental forces is able to manage the above problems.

The control laws are given by

$$T_m = K_{Pm}\left[\frac{1}{k_p}q_s(t-T) - q_m\right] + K_D\left[\frac{1}{k_p}\dot{q}_s(t-T) - \dot{q}_m\right] - B_m\dot{q}_m + \theta\hat{F}_h + g_m \tag{4}$$

$$T_s = K_{Ps}\left[q_s - k_p q_m(t-T)\right] + K_D\left[k_p\dot{q}_m - \dot{q}_s(t-T)\right] + B_s\dot{q}_s + \theta\hat{F}_e - g_s \tag{5}$$

where $\mathrm{K_{Pm}}$, $\mathrm{K_{Ps}}$, K_D, $\mathrm{B_m}$ and $\mathrm{B_s}$ are positive definite matrices in $R^{n\times n}$; $\hat{F}_h$ and $\hat{F}_e$ are the estimated operator and environmental forces;$\theta$is the coefficient of estimated forces that is between zero and one; and $k_p$is the position scale factor.

3.1. Force estimation algorithm

A general nonlinear dynamic model of manipulators can be written as

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = T + F \tag{6}$$

The following algorithm is proposed for external force estimation:

$$\dot{\hat{F}} = -L\hat{F} + L\left[M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) - T\right] \tag{7}$$

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