Research Article

An Adaptive Regulator for Space Teleoperation System in Task Space

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The problem of the gravity information which can not be obtained in advance for bilateral teleoperation is studied. In outer space exploration, the gravity term changes with the position changing of the slave manipulator. So it is necessary to design an adaptive regulator controller to compensate for the unknown gravity signal. Moreover, to get a more accurate position tracking performance, the controller is designed in the task space instead of the joint space. Additionally, the time delay considered in this paper is not only time varying but also unsymmetrical. Finally, simulations are presented to show the effectiveness of the proposed approach.

1. Introduction

A teleoperation system can extend the human-sensing and manipulative capabilities to the remote environment. Now the teleoperation system has been used in many areas, for instance, outer space operation, robotic telesurgery, handling of toxic, and harmful materials, and underwater exploration [1–3].

In bilateral teleoperation system, the master and the slave manipulators are connected via a long communication network. So the time delay cannot be ignored. It has been noticed that the presence of time delay can influence the system performance. And it can even destabilize a stable system. It is recognized that Anderson and Spong [4] proposed the first delay independent controller for constant time delays via the scattering transformation. Later, the wave variables method was introduced [5]. Then the wave variables method had been improved by many papers [6–8]. However, it is necessary to recognize the fact that the classic scattering transformation may lead to position drift. Then a proportional derivative plus damping (PD+d) controller was proposed in [9] and the scattering transformation approach was discarded. Later, a simple proportional plus damping (P+d) controller was proposed in [10]. However, the time

delay considered in this paper was constant. In [11], the model-free linear observer-based PD output feedback control design was used to solve the output feedback stabilization for industrial robotic systems. Reference [12] presented a hybrid control strategy for the trajectory tracking control problem of robotic manipulators. The use of Internet for teleoperation communication provides obvious benefits. Nevertheless, the time delay caused by Internet communication channel is not only time varying but also unsymmetrical. Time delay has become an unavoidable factor affecting the stability of closed-loop system [13–17].

Thanks to [18, 19], a simple P+d controller can ensure position tracking and asymptotic convergence to zero of velocities in the presence of variable time delays.

Comparing with other control methods, the PD controller has irreplaceable advantages. Owing to its simple structure and easy implementation, it has been used extensively. However, in [9–12], it is easy to see that an assumption was needed before designing the controller, in which the gravity information can be achieved in advance. However, in many practical applications, it is a serious restriction for the application of PD controller in teleoperation system. Moreover, this issue arises for the teleoperation applications of the robots in the outer space. In outer space, different

locations have different gravity acceleration. However, with more and more advanced technology, it is possible to detect the gravity. It is expensive and may take a long time and it cannot adapt to the requirements of real-time control. So an adaptive regulator is necessary.

In the existing literatures about the teleoperation system, most controllers were designed in joint space. And the objectives of most papers were to design a controller to make the joint position error between the master and the slave convergence to zero. However, the ultimate aim of using teleoperation is to make the slave complete a certain job under the control of the human operator. And the job is completed by the terminal actuator. It is necessary to notice the phenomenon where the master and the slave manipulators have different joint lengths and joint mass and even different dynamics models may exist. Under this phenomenon, the joint synchronization cannot guarantee the terminal actuator synchronization. This situation can be avoided with the controller designing in the task space [20].

In some literatures for space teleoperation [21–24], the gravity term was directly neglected when the gravity acceleration was zero. In this paper, we consider the situation that gravity information cannot be obtained. An adaptive regulator is added in the typical P+d controller to compensate for the unknown gravity signal. Moreover, to make the slave manipulator complete its job accurately under domination of the human operator, the controller is designed in task space. Consider the Internet communication channel; the time delay considered in our paper is time varying and asymptotical.

This paper is organized as follows. Section 2 presents the modeling framework and the related properties and assumptions. The controller is proposed and the stability analysis is deprived in Section 3. In Section 4, some simulation results are applied to prove the effectiveness of the approach. Finally, some conclusion will be provided and some future work will be mentioned.

2. Problem Formulation

Consider a master-slave bilateral teleoperation system modeled as a pair of n-degree-of-freedom (DOF) serial links with revolute joints. The nonlinear dynamics are presented as

$$M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + G_m(q_m) = \tau_m - J_m^T(q_m)F_h,$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + G_s(q_s) = J_s^T(q_s)F_e - \tau_s,$$

$$(1)$$

where m represents the master manipulator and s represents the slave manipulator. $q_m(t), q_s(t) \in \mathbb{R}^n$ are the vectors of the joint displacements; $\dot{q}_m(t), \dot{q}_s(t) \in \mathbb{R}^n$ are the vectors of joint velocities; $\ddot{q}_m(t), \ddot{q}_s(t) \in \mathbb{R}^n$ are the vectors of joint accelerations; $M_m(q_m), M_s(q_s) : \mathbb{R}^n \rightarrow \mathbb{R}^{n\times n}$ are the positive definite inertia matrices; $C_m(q_m,\dot{q}_m), C_s(q_s,\dot{q}_s) : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^{n\times n}$ are the matrices of centripetal and coriolis torques; $G_m(q_m), G_s(q_s) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ are the gravitational torques; $F_h, F_e \in \mathbb{R}^n$ are the human operator force and the environment force, respectively; $J_m(q_m), J_s(q_s) \in \mathbb{R}^{n\times n}$ are the

Jacobian matrices for the master manipulator and the salve manipulator; $\tau_m, \tau_s \in \mathbb{R}^n$ are the applied torques.

Here the following assumption for Jacobian matrix $J_i(q_i)$ $(i = m, s)$ is introduced.

Assumption 1. The Jacobian matrix $J_i(q_i)$ $(i = m, s)$ should be nonsingular.

Remark 2. As we all know, in reality industry production, the singularity problem may exist in the Jacobian matrix. Then the $\|J_i(q_i)\| \rightarrow \infty$ and the torque of system will tend to infinity when there exists singularity in Jacobian matrix. Thanks to the new technology, this situation can be avoided by institutional design and trajectory planning. So this assumption in this paper is reasonable.

It is well known that the work space of manipulator can be transformed from joint space to task space with a nonsingular Jacobian matrix. So we have

$$x_i = h_i(q_i),$$

$$\dot{x}_i = J_i(q_i)\dot{q}_i,$$

$$\ddot{x}_i = \dot{J}_i(q_i)\dot{q}_i + J_i(q_i)\ddot{q}_i,$$

$$(2)$$

where x_i is the joint position in task space and $i = m, s$.

For the sake of simplicity, the arguments of functions are eliminated hereafter. And the master and slave robot dynamics in the task space are presented as follows:

$$M_{tm}\ddot{x}_m + C_{tm}\dot{x}_m + G_{tm} = J_m^{-T}\tau_m - F_h,$$

$$M_{ts}\ddot{x}_s + C_{ts}\dot{x}_s + G_{ts} = F_e - J_s^{-T}\tau_s,$$

$$(3)$$

where

$$M_{tm} = J_m^{-T}M_m J_m^{-1},$$

$$M_{ts} = J_s^{-T}M_s J_s^{-1},$$

$$C_{tm} = J_m^{-T}\left(C_m - M_m J_m^{-1}\dot{J}_m\right)J_m^{-1},$$

$$C_{ts} = J_s^{-T}\left(C_s - M_s J_s^{-1}\dot{J}_s\right)J_s^{-1},$$

$$G_{tm} = J_m^{-T}G_m,$$

$$G_{ts} = J_s^{-T}G_s.$$

$$(4)$$

Below, fundamental properties of the master and slave manipulators needed in the subsequent analysis are presented.

Property 1. The inertia matrix $M_{ti}(q)$ is positive definite function, and there exist positive constants m_1 and m_2 such that

$$m_1 I \le M_{ti}(q) \le m_2 I. \tag{5}$$

Property 2. The matrix $\dot{M}_{ti}(q) - 2C_{ti}(q,\dot{q})$ is skew-symmetric.

Property 3. For all $q_i, x, y \in R^{n\times 1}$, there exists a positive scalar α_i such that $\|C_i(q,x)y\| \le \alpha_i\|x\|\|y\|$.

Property 4. The gravity functions G_{tm} and G_{ts} can be linearized and can be expressed as $G_{tm}(q_m) = Y_m a_m$ and $G_{ts}(q_s) = Y_s a_s$, where Y_m and Y_s are known nonlinear functions and usually are called regressor matrices, while a_m and a_s are unknown vectors.

The following standard assumptions are imposed on the teleoperation system.

Assumption 3. The variable time delay has an upper bound $\overline{T}_i$; that is, $0 \leq T_i(t) \leq \overline{T}_i \leq \infty$, $i = m, s$.

Assumption 4. Following standard considerations, we assume that the human operator and the environment are passive (force to velocity) maps; that is, there exist scalars $\kappa_i \in R_0^+$ such that for all $t \geq 0$

$$\int_0^t \dot{x}_m^T F_h d\sigma \geq -\kappa_m, \qquad -\int_0^t \dot{x}_s^T F_e d\sigma \geq -\kappa_s. \tag{6}$$

Before proposing the controller, the following lemma is needed.

Lemma 5. For any vector signals x, y, any variable time delay $0 \leq T_i(t) \leq \overline{T}_i \leq \infty$, and constant $\alpha > 0$, one has

$$-2 \int_0^t x^T(\sigma) \int_{-T_i(\sigma)}^0 y(\sigma + \theta) d\theta d\sigma \leq \alpha \|x\|_2^2 + \frac{\overline{T}_i^2}{\alpha} \|y\|_2^2. \tag{7}$$

3. Controller Design

In original researches, little attention was paid to the gravity term; moreover, they even made the assumption that the gravity can be accurately obtained in advance. However, in many cases, the gravity not only cannot be accurately obtained directly, but also cannot be measured. This issue arises for the teleoperation applications of the robots in the outer space. It is well known that the gravity coefficient g is different for the earth, outer space, and the moon. The above two issues may render that the precise value of parameter g is not known for teleoperation. In this section, we consider this problem and propose a new controller combining a typical P+d controller and an adaptive regulator.

Without the accurate gravity information, the new direct force-feedback controller combined with the estimate gravity information is designed as follows:

$$\tau_m = J_m^T \left[K_m \left(x_s \left(t - T_s(t) \right) - x_m \right) - B_m \dot{x}_m + \widehat{G}_{tm} \right],$$
$$\tau_s = J_s^T \left[K_s \left[x_s - x_m \left(t - T_m(t) \right) \right] + B_s \dot{x}_s - \widehat{G}_{ts} \right], \tag{8}$$

where K_m, K_s, B_m, and B_s are positive constant scalars and the $\widehat{G}_{tm}$ and $\widehat{G}_{ts}$ are the estimations for G_{tm} and G_{ts}, respectively. In addition, they are described as follows:

$$\widehat{G}_{tm} = Y_m \widehat{a}_m,$$
$$\widehat{G}_{ts} = Y_s \widehat{a}_s, \tag{9}$$

where $\widehat{a}_m(t)$ and $\widehat{a}_s(t)$ are the adaptive matrices with the tuning laws as

$$\dot{\widehat{a}}_m(t) = -\Gamma_m Y_m \dot{x}_m^T,$$
$$\dot{\widehat{a}}_s(t) = -\Gamma_s Y_s \dot{x}_s^T, \tag{10}$$

where Γ_m and Γ_s are positive definite matrices.

Theorem 6. For the teleoperation system (1) *controlled by* (8) *with Assumptions 1–4, the closed-loop system is stable with the tuning laws* (10) *and the following condition holds:*

$$2B_m B_s > K_m K_s \left(\overline{T}_m^2 + \overline{T}_s^2 \right). \tag{11}$$

And the velocity and position errors are bounded (i.e., $\dot{x}_i, x_m - x_s \in \ell_\infty$) and $\dot{x}_i \in \ell_2$; moreover $|x_m - x_s(t - T_s(t))| \in \ell_\infty$.

Proof. Let us consider the Lyapunov function candidates:

$$V_1 = \frac{1}{2} \dot{x}_m^T M_{tm} \dot{x}_m + \frac{K_m}{2K_s} \dot{x}_s^T M_{ts} \dot{x}_s + \frac{K_m}{2} |(x_m - x_s)|^2$$
$$+ \int_0^t \left(\dot{x}_m^T F_h - \frac{K_m}{K_s} \dot{x}_s^T F_e \right) d\sigma + k_m + \frac{K_m k_s}{K_s}, \tag{12}$$

$$V_2 = \frac{1}{2} \widetilde{a}_m^T \Gamma_m^{-1} \widetilde{a}_m + \frac{K_m}{2K_s} \widetilde{a}_s^T \Gamma_s^{-1} \widetilde{a}_s, \tag{13}$$

where $\widetilde{a}_m = \widehat{a}_m - a_m$ and $\widetilde{a}_s = \widehat{a}_s - a_s$.

Property 1 and Assumption 4 guarantee that the function V_1 is positive definite and it is obvious that V_2 is also positive definite with the positive Γ_m and Γ_s.

The derivative of the above function V_1 is presented as follows:

$$\dot{V}_1 = \dot{x}_m^T \left(-C_{tm} \dot{x}_m - G_{tm} + J_m^{-T} \tau_m - F_h \right) + \frac{1}{2} \dot{x}_m^T \dot{M}_{tm} \dot{x}_m$$
$$+ \frac{K_m}{K_s} \dot{x}_s^T \left(-C_{ts} \dot{x}_s - G_{ts} + F_e - J_s^{-T} \tau_s \right) + \frac{1}{2} \dot{x}_s^T \dot{M}_{ts} \dot{x}_s$$
$$+ K_m \left(\dot{x}_m - \dot{x}_s \right) \left(x_m - x_s \right) + \dot{x}_m^T F_h - \frac{K_m}{K_s} \dot{x}_s^T F_e; \tag{14}$$

with Property 2 and the new controller (11) the subsequent equation can be given as

$$\dot{V}_1 = \dot{x}_m^T \left[K_m \left(x_s \left(t - T_s(t) \right) - x_m \right) - B_m \dot{x}_m + \widetilde{G}_{tm} \right]$$
$$+ \frac{K_m}{K_s} \dot{x}_s^T \left[K_s \left[x_m \left(t - T_m(t) \right) - x_s \right] - B_s \dot{x}_s + \widetilde{G}_{ts} \right]$$
$$+ K_m \left(\dot{x}_m^T - \dot{x}_s^T \right) \left(x_m - x_s \right)$$
$$= -\dot{x}_m^T B_m \dot{x}_m - \frac{K_m}{K_s} \dot{x}_s^T B_s \dot{x}_s + \dot{x}_m^T K_m \left(x_s \left(t - T_s(t) \right) - x_s \right)$$
$$+ \dot{x}_s^T K_m \left(x_m \left(t - T_m(t) \right) - x_m \right) + \dot{x}_m^T \widetilde{G}_{tm} + \frac{K_m}{K_s} \dot{x}_s^T \widetilde{G}_{ts}, \tag{15}$$

where $\widetilde{G}_{tm} = \widehat{G}_{tm} - G_{tm} = Y_m(\widehat{a}_m - a_m)$ and $\widetilde{G}_{ts} = \widehat{G}_{ts} - G_{ts} = Y_s(\widehat{a}_s - a_s)$. With the following equation:

$$x_i\left(t - T_i\left(t\right)\right) - x_i\left(t\right) = -\int_{-T_i(t)}^{0} \dot{x}_i\left(t + \theta\right) d\theta, \qquad (16)$$

we can get

$$\dot{V}_1 = -B_m\left|\dot{x}_m\right|^2 - \frac{K_m}{K_s}B_s\left|\dot{x}_s\right|^2 - K_m\dot{x}_m^T\int_{-T_s(t)}^{0} \dot{x}_s\left(t + \theta\right) d\theta$$

$$- K_m\dot{x}_s^T\int_{-T_m(t)}^{0} \dot{x}_m\left(t + \theta\right) d\theta + \dot{x}_m^T\widetilde{G}_{tm} + \frac{K_m}{K_s}\dot{x}_s^T\widetilde{G}_{ts}. \qquad (17)$$

The derivative of the above function V_2 is given as follows:

$$\dot{V}_2 = \widetilde{a}_m^T\Gamma_m^{-1}\dot{\widehat{a}}_m + \widetilde{a}_s^T\Gamma_s^{-1}\dot{\widehat{a}}_s \qquad (18)$$

with the adaptive tuning law (11) yielding

$$\dot{V}_2 = \widetilde{a}_m^T\Gamma_m^{-1}\left(-\Gamma_m Y_m\dot{x}_m\right) + \frac{K_m}{K_s}\widetilde{a}_s^T\Gamma_s^{-1}\left(-\Gamma_s Y_s\dot{x}_s\right)$$

$$= -\left(Y_m\widetilde{a}_m\right)^T\dot{x}_m - \frac{K_m}{K_s}\left(Y_s\widetilde{a}_s\right)^T\dot{x}_s,$$

$$\dot{V} = \dot{V}_1 + \dot{V}_2 = -B_m\left|\dot{x}_m\right|^2 - \frac{K_m}{K_s}B_s\left|\dot{x}_s\right|^2 \qquad (19)$$

$$- K_m\dot{x}_m^T\int_{-T_s(t)}^{0} \dot{x}_s\left(t + \theta\right) d\theta$$

$$- K_m\dot{x}_s^T\int_{-T_m(t)}^{0} \dot{x}_m\left(t + \theta\right) d\theta.$$

Now let us invoke Lemma 5 to obtain a bound on the integral of $\dot{V}$. Toward this end, integrate the above equation from 0 to t, yielding

$$V\left(t\right) - V\left(0\right) \le -B_m\left\|\dot{x}_m\right\|^2 - \frac{K_m}{K_s}B_s\left\|\dot{x}_s\right\|^2$$

$$+ \frac{K_m\beta_m}{2}\left\|\dot{x}_m\right\|^2 + \frac{K_m\overline{T}_s^2}{2\beta_m}\left\|\dot{x}_s\right\|^2$$

$$+ \frac{K_m\beta_s}{2}\left\|\dot{x}_s\right\|^2 + \frac{K_m\overline{T}_m^2}{2\beta_s}\left\|\dot{x}_m\right\|^2 \qquad (20)$$

$$= -\left(B_m - \frac{K_m\beta_m}{2} - \frac{K_m\overline{T}_m^2}{2\beta_s}\right)\left\|\dot{x}_m\right\|^2$$

$$- \left(\frac{K_m}{K_s}B_s - \frac{K_m\beta_s}{2} - \frac{K_m\overline{T}_s^2}{2\beta_m}\right)\left\|\dot{x}_s\right\|^2.$$

Thus, satisfying condition (12) with the nonnegativity of V, $\dot{x}_i \in \ell_2$ can be proved; moreover, $\dot{x}_i, x_m - x_s \in \ell_\infty$ and $|x_m - x_s(t - T_s(t))| \in \ell_\infty$ can be proved. $\qquad \square$
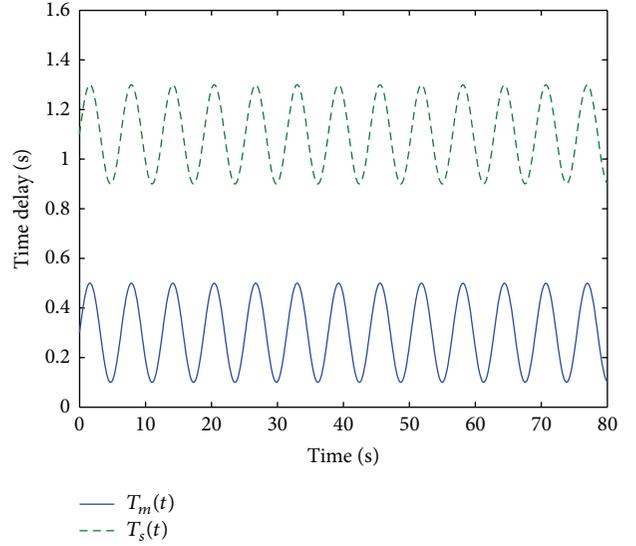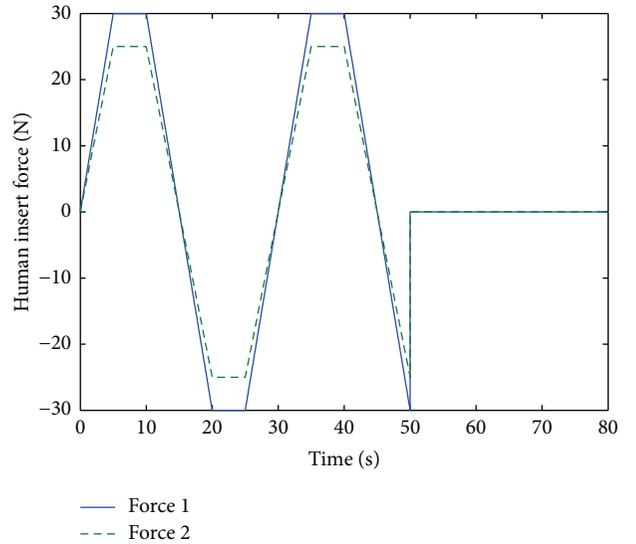

FIGURE 1: The time delay.

FIGURE 2: The human insert force.

Remark 7. In this paper, we consider the situation that gravity information cannot be obtained. An adaptive regulator is added in the typical P+d controller to compensate for the unknown gravity signal.

Remark 8. In order to make the slave manipulator complete its job accurately under domination of the human operator, the controller is designed in task space. Consider the Internet communication channel; the time delay considered in this paper is time varying and asymptotical.

Remark 9. From the above proof, we can see that the adaptive tuning law is derived in the paper. Therefore, we can obtain less conservative result by optimizing these parameters.
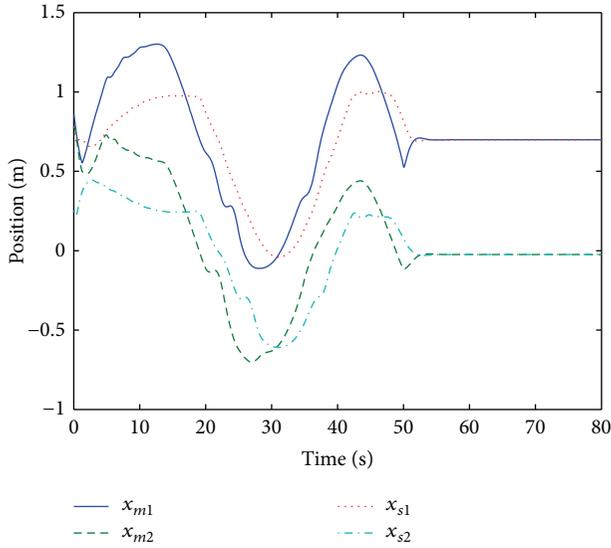
FIGURE 3: The positions of the master and the slave in task space with the known gravity term.
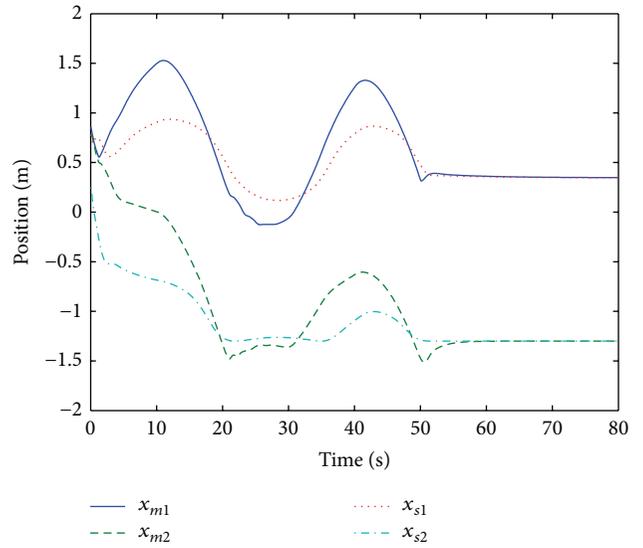

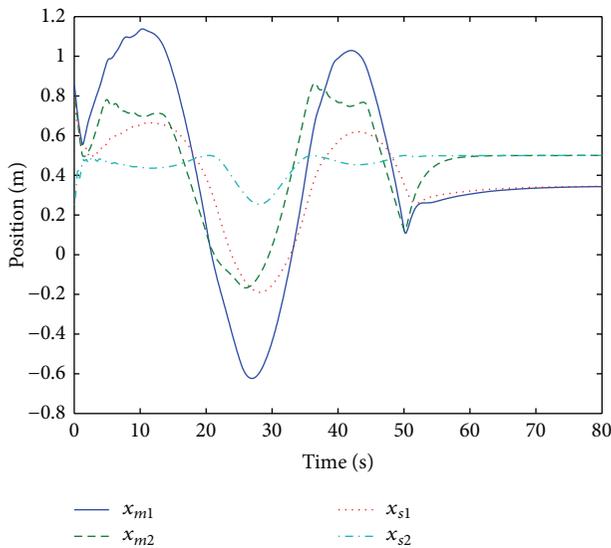FIGURE 5: The positions of the master and the slave in task space with adaptive regulator.

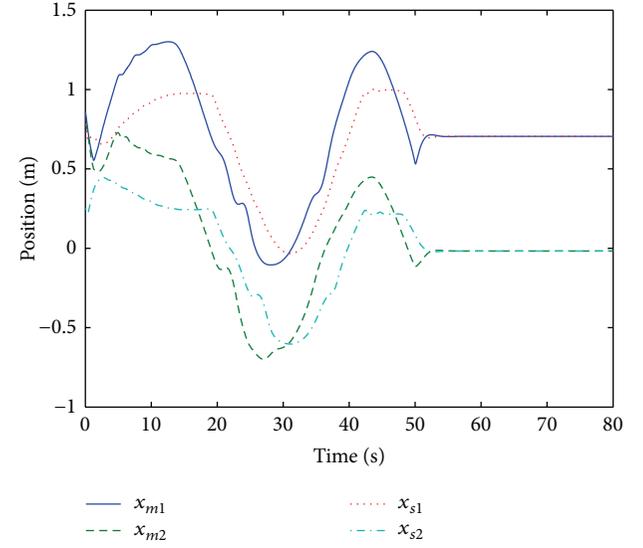FIGURE 4: The positions of the master and the slave in task space without adaptive regulator.

FIGURE 6: The positions of the master and the slave in task space with the known gravity term.

The numerical example given in the next part shows the effectiveness of our result.

4. Simulations

In order to show the effectiveness of the proposed scheme, in this section some simulations are presented in which the local and remote manipulators are modeled as a pair of 2 DOF serial links.

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) = \tau_m - J_m^T(q_m)F_h,$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) = J_s^T(q_s)F_e - \tau_s,$$

$$\tag{21}$$

where

$$M_m(q) = M_s(q) = \begin{bmatrix} M_{11} & M_{12} \\ * & M_{22} \end{bmatrix},$$

$$C_m(q, \dot{q}) = C_s(q, \dot{q}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}, \tag{22}$$

$$G_m(q) = G_s(q) = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$$

in which

$$M_{11} = (2l_1 \cos(q_2) + l_2) l_2 m_2 + l_1^2 (m_1 + m_2),$$

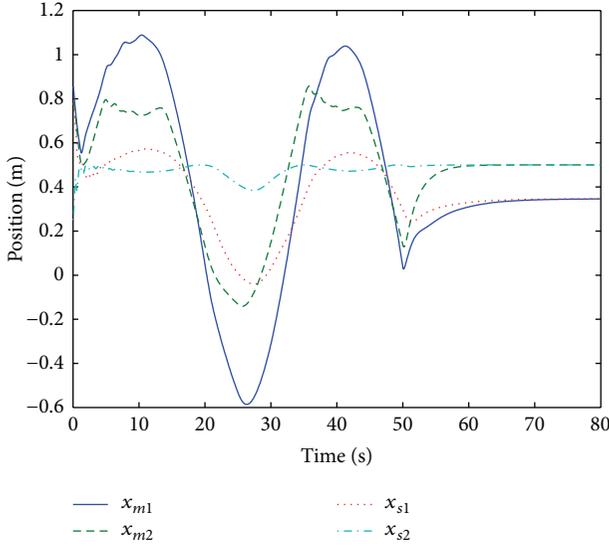$$M_{12} = l_2^2 m_2 + l_1 l_2 m_2 \cos(q_2),$$

FIGURE 7: The positions of the master and the slave in task space without adaptive regulator.
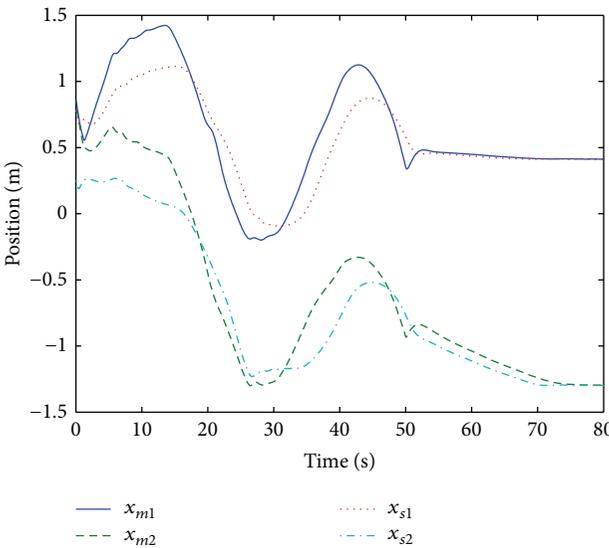

FIGURE 8: The positions of the master and the slave in task space with adaptive regulator.

$$
\begin{aligned}
M_{21} &= M_{12}, \\
M_{22} &= l_2^2 m_2, \\
C_{11} &= -l_1 l_2 m_2 \sin(q_2)\, \dot{q}_2, \\
C_{12} &= -l_1 l_2 m_2 \sin(q_2)(\dot{q}_1 + \dot{q}_2), \\
C_{21} &= l_1 l_2 m_2 \sin(q_2)\, \dot{q}_1, \\
C_{22} &= 0, \\
G_1 &= g\left(m_2 l_2 \cos(q_1 + q_2) + (m_1 + m_2)\, l_1 \cos(q_1)\right), \\
G_2 &= g m_2 l_2 \cos(q_1 + q_2).
\end{aligned}
\tag{23}
$$

The manipulator Jacobian matrix $J_i(q_i)$ mapping from joint space to task space is given as

$$
J_i = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}
\tag{24}
$$

in which

$$
\begin{aligned}
J_{11} &= -l_1 \sin(q_1) - l_2 \sin(q_1 + q_2), \\
J_{12} &= -l_2 \sin(q_1 + q_2), \\
J_{21} &= l_1 \cos(q_1) + l_2 \cos(q_1 + q_2), \\
J_{22} &= l_2 \cos(q_1 + q_2).
\end{aligned}
\tag{25}
$$

Moreover, with the detailed definition of a_m^T, a_s^T, Y_m, and Y_s, G_{tm} and G_{ts} can follow this definition:

$$
G_t = J^{-T} \begin{bmatrix} \cos(q_1 + q_2) & \cos(q_1) \\ \cos(q_1 + q_2) & 0 \end{bmatrix} \begin{bmatrix} g m_2 l_2 \\ g l_1 (m_1 + m_2) \end{bmatrix}.
\tag{26}
$$

For simulation, in the master manipulator we choose the parameters $m_1 = 10\,\text{kg}$, $m_2 = 7\,\text{kg}$, $l_1 = 0.7\,\text{m}$, and $l_2 = 0.5\,\text{m}$ and the master manipulator usually placed in the laboratory; therefore, we can set the $g = 9.81\,\text{m/s}^2$. The slave manipulator parameters are $m_1 = 7\,\text{kg}$, $m_2 = 5\,\text{kg}$, $l_1 = 0.5\,\text{m}$, $l_2 = 0.4\,\text{m}$, and $g = 0.2\,\text{m/s}^2$. The controller parameters are set as $Km = 20$, $B_m = 40$, $Ks = 40$, $Bs = 60$, and $\Gamma_s = 0.1$. The initial joint configurations of the master and slave are set as $x_m(0) = [0.7830\ 0.8562]^T$ and $x_s(0) = [0.7794\ 0.25]^T$. The simulation results are used to verify the following: when we move the master robot, does the slave manipulator follow the master manipulator? Based on Theorem 6, the delays are set as $T_m(t) = 0.3 + 0.2\sin(t)$ and $T_s(t) = 1.1 + 0.2\sin(t)$. Figure 1 shows the time delay we set in this paper. The human operation inserting forces are presented in Figure 2. Figure 3 shows the positions of x_m and x_s when the gravity term can be obtained in advance and $g = 5\,\text{m/s}^2$. Figure 4 shows the positions of x_m and x_s without the adaptive regulator and $g = 5\,\text{m/s}^2$. Figure 5 shows the positions of x_m and x_s with the adaptive regulator and $g = 5\,\text{m/s}^2$. Figure 6 shows the positions of x_m and x_s when the gravity term can be obtained in advance and $g = 1\,\text{m/s}^2$. Figure 7 shows the positions of x_m and x_s without the adaptive regulator and $g = 1\,\text{m/s}^2$. Figure 8 shows the positions of x_m and x_s with the adaptive regulator and $g = 1\,\text{m/s}^2$.

From Figure 3, we can see that the slave moves with the master when the gravity term is known in advance. However, in Figure 4, without the adaptive regulator, the slave does not move with the master, specially, in the x_{s2} direction. In Figure 5, the problem is solved by applying the new controller we proposed in this paper. By comparing Figures 7 and 8, we also can get the same conclusion.

5. Conclusion

In this paper, the case that the gravity term cannot be obtained is considered in outer space exploration. An adaptive regulator is proposed to compensate for the unknown gravity term. By proposing the proper Lyapunov function, the adaptive tuning law is also derived in our paper. Moreover, the simulation results prove the effectiveness of our controller. In this paper, we consider that the Jacobian matrix is accurately known. However, in some cases, the Jacobian matrix cannot be known. Therefore, in the future, we will consider using adaptive theory to estimate the unknown Jacobian matrix.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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