Transparency Improvement by External Force Estimation in a Time-Delayed Nonlinear Bilateral Teleoperation System

Teleoperation systems have been developed in order to manipulate objects in environments where the presence of humans is impossible, dangerous or less effective. One of the most attractive applications is micro telemanipulation with micropositioning actuators. Due to the sensitivity of this operation, task performance should be accurately considered. The presence of force signals in the control scheme could effectively improve transparency. However, the main restriction is force measurement in micromanipulation scales. A new modified strategy for estimating the external forces acting on the master and slave robots is the major contribution of this paper. The main advantage of this strategy is that the necessity for force sensors is eliminated, leading to lower cost and further applicability. A novel control algorithm with estimated force signals is proposed for a general nonlinear macro–micro bilateral teleoperation system with time delay. The stability condition in the macro–micro teleoperation system with the new control algorithm is verified by means of Lyapunov stability analysis. The designed control algorithm guarantees stability of the macro–micro teleoperation system in the presence of an estimated operator and environmental force. Experimental results confirm the efficiency of the novel control algorithm in position tracking and force reflection. [DOI: 10.1115/1.4029077]

1 Introduction

Teleoperation systems have become an extensive and interesting field for researchers in the last decade. The main function of teleoperation systems is to operate from a remote location [1,2]. A useful application of teleoperation systems is to control a robotic vehicle in hazardous situations. Other applications include telesurgery, space technology, and underwater exploration [3–5]. A new emerging application area is called macro–micro teleoperation where the operator is restricted in directly manipulating micro objects. Macro–micro teleoperation systems enable the manipulation of tasks in the microworld. Smart actuators, such as the piezoelectric stage, have been widely used as slave manipulators in applications of macro–micro manipulation [6–10]. In bilateral teleoperation systems, the main purpose is to control the remote manipulator and sense the forces exerted on the robot in a remote environment. Therefore, stability and transparency are two
prominent objectives that should be satisfied. Transparency in a teleoperation system is investigated by measuring the impedance, which is transmitted to the operator through the environment.

Conventional teleoperation system controllers use position and velocity signals of master and slave robots [11–14]. In these approaches, position tracking is disturbed when the slave robot is in contact with the environment. In fact, position error between the master and slave is inevitable in these control schemes. Such error deteriorates the transparency of the closed-loop teleoperation system.

Transparency can be enhanced if force signals are transmitted in addition to position and velocity signals. Therefore, a four-channel architecture teleoperation system is ideal to achieve both perfect tracking and force reflection simultaneously, since the operator would have a better sense of the environment.

To improve system transparency, force signals have been applied in the control structure in addition to position and velocity signals. Therefore, a four-channel architecture teleoperation system stability is considered. Stability analysis is only achieved for the linear bilatera teleoperation system; but in many robotic tasks the dynamic model is nonlinear. In addition, measuring external force signals in various robotic tasks is also not feasible due to the high cost of force sensors. The associated noises are also high and force sensor installation may be difficult. Eliminating the force sensors is achieved by estimating the external forces acting on the master and slave robots [18–21]. The estimation of external forces is presented on the master and slave in combination with a modified version of the sliding mode bilateral teleoperation algorithm [18,19]. The main drawback is that the force reflecting from the closed-loop system is not considered, whereas force reflection is one of the most important purposes of bilateral teleoperation systems. A synchronization scheme of bilateral teleoperation by using a state observer has also been proposed for improvement [20]. However, reliable force synchronization has not been achieved. In Ref. [21], it was experimentally proven that external force is estimated but it is not analytically demonstrated. The other drawback is that transparency in the control system is not considered. Another problem concerning these force estimation algorithms is that employing them may not guarantee the stability of closed-loop systems. In the present paper, a novel control scheme is proposed for a nonlinear bilateral macro–micro teleoperation system with the presence of constant time delays. The difference between this proposed control scheme and common controllers used for nonlinear macro–micro teleoperation systems is the existence of force signals in the control scheme. To remove force measurement, a new, modified force estimation algorithm is proposed. Stability and transparency of the closed-loop macro–micro teleoperation system with the existence of estimated forces is proven by the Lyapunov stability criteria. Experimental results validate the performance of nonlinear bilateral macro–micro teleoperation. Moreover, precise tracking in free motion and when the slave is in contact with the environment is achieved. Force reflection is also appropriately satisfied, as the major achievement of this work. The results confirm that the estimated external forces suitably converge to real external forces. In addition, this proposed control scheme is experimentally compared with the common controller. It is demonstrated that the transparency of the nonlinear teleoperation system has improved.

2 Model Definition

The dynamic model of a macro–micro teleoperation system is considered as

\[
M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + g_m(q_m) = T_m - F_h
\]

(1)

\[
M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + g_s(q_s) = F_s - T_s
\]

(2)

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

The properties of the dynamic model of robotic manipulators with rotational joints are used as follows:

\[ P1: M_s(q_s) = C_s(q_s, \dot{q}_s) + \frac{\partial}{\partial q_s}H(q_s, \dot{q}_s) \]

\[ P2: \exists \beta_i, \beta_i \in \mathbb{R}^n \text{ such that } \beta_i^T \beta_i \leq M_s(q_s) \leq \beta_i^T \beta_i \]

\[ P3: \text{for all } q_i, x, y \in \mathbb{R}^n, \exists \beta_i \in \mathbb{R}^n \text{ such that } |C_i(q_i, x)| \leq \kappa_i|x||y|, \text{ where } |.| \text{ is the Euclidean norm.} \]

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

Before describing the proposed control scheme and discussing its advantage, previous common control schemes are explored.

3 Transparency Analysis of Different Teleoperation Control Systems With the Slave Robot in Contact

In this section, a comparison between the common (Two-Channel Control Architectures) and (Two-Channel Control Architectures + Locally External Force Signals) and the proposed control scheme (Two-Channel Control Architectures + Globally External Force Signals) is investigated for a nonlinear teleoperation system.

In two-channel control architectures, one signal from the master side is sent to the slave controller and one signal from the slave robot is transmitted back to the master. The type of transmitted signals could be external force and position. Performance tools are introduced in this section to analyze the commonly used two-channel architecture, namely, position–position (P–P), position–force (P–F), and force–force (F–F)’s. The position signal of the master robot is sent to the slave controller and slave robot’s position is transmitted to the master controller.

3.1 Two-Channel Control Architectures. First, position–position (P–P) architecture in the bilateral control is investigated that was implemented [12]. A schematic figure of this architecture is shown in Fig. 1.

The control scheme is as follows:

\[ T_m = K_m(q_m(t - T) - q_m) - B_nq_m + g_m \]

\[ T_s = K_s[q_s(t - T) - q_m] + B_n\dot{q}_s - g_s \]

(3)

(4)

It has been proven that the position error in free motion converges to zero [12]. When the slave robot is in contact with the environment, the position error in steady-state condition is specified by

\[ q_s - q_m = \frac{F_h}{K_m} \]

\[ q_s - q_m = \frac{F_s}{K_s} \]

(5)

(6)

If \(K_m = K_s\), it can be concluded that force reflection has occurred. But in contact, the error of position is proportional to the external forces. As a result, it could be deduced that with this control scheme position tracking does not occur in contact.

To validate this claim, a simulation study for a one degree-of-freedom (DOF) system was performed. The schematic figure of this system is shown in Fig. 2, which illustrates that the master and slave robot is composed of mass, damper, and spring, and the environment going into contact with the slave robot consists of mass and a high-stiffness spring. The values used in the simulation study are given in Table 1.

The controller gains utilized in the simulation study are mentioned in Table 2. In addition, the value of the considered time delay is 0.2 s.
The results are related to the control scheme presented in Eqs. (3) and (4) and are shown in Fig. 3. Figure 3(a) indicates the position tracking of the master and slave robots in free motion and when the slave robot is in contact with the environment. According to this figure, it is observed that the position tracking of the master and slave deteriorates during contact motion. Figure 3(b) shows that when the slave robot is in contact with the environment, force reflection is satisfied. The values of the control inputs are shown in Fig. 4.

3.2 Two-Channel Control Architectures + Local External Force Signals. To reduce the position error in the mentioned control scheme, external forces are used locally in the control scheme as an alternative approach. This architecture is presented in Fig. 5. The control scheme is as follows:

\[
T_m = K_m[q_s(t-T) - q_m] - B_m\dot{q}_m + \theta F_h + g_m \quad (7)
\]
\[
T_s = K_s[q_s(t-T)] + B_s\dot{q}_s + \theta F_e - g_s \quad (8)
\]

where \(\theta\) is the coefficient of human and environmental forces used in the control scheme. This coefficient could vary between zero and one \((0 < \theta < 1)\). The nonlinear bilateral teleoperation in the presence of this control scheme is investigated. When the slave robot collides with the environment the error of position is

\[
q_s - q_m = \frac{(1-\theta)F_h}{K_m} \quad (9)
\]
\[
q_s - q_m = \frac{(1-\theta)F_e}{K_s} \quad (10)
\]

According to Eqs. (9) and (10), force reflection occurred and the error of position diminished as compared to the previous control scheme. This error is proportional to the coefficient of the external forces applied in the control scheme. It is obvious that the position error tends toward zero with increasing the coefficient \(\theta\), but it might lead to input saturation in the control structure. Therefore, a tradeoff between position error and control effort should be considered. The simulation results for this condition are presented in Fig. 6.

According to Figs. 3 and 6, it seems that when external force signals are locally imported to the control scheme, the position error is reduced. The respective error values are shown in Fig. 7. As expected, the position error diminished as a result of external force signals in the control scheme.

The control scheme values are shown in Fig. 8.

3.3 Two-Channel Control Architectures + Global External Force Signals. The human and environmental forces are now imported in the control scheme globally. Figure 9 shows the schematic of this condition.

### Table 1 Values used in the simulation

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>Damper (Ns/m)</th>
<th>Spring (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master</td>
<td>1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Slave</td>
<td>1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Environment</td>
<td>50</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 Values for the controller gains

<table>
<thead>
<tr>
<th></th>
<th>Control gains of the master robot</th>
<th>Control gains of the slave robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_m)</td>
<td>550</td>
<td>(K_s) = 550</td>
</tr>
<tr>
<td>(B_m)</td>
<td>80</td>
<td>(B_s) = 80</td>
</tr>
<tr>
<td>(g_m)</td>
<td>10</td>
<td>(g_s) = 10</td>
</tr>
</tbody>
</table>
The control scheme is specified by

\[ T_m = K_m (q_s(t) - q_m) - B_m \dot{q}_m + F_c(t - T) + g_m \]  
\[ T_s = K_s (q_s - q_m(t - T)) + B_s \dot{q}_s + F_h(t - T) - g_s \]  

(11)  
(12)

The closed-loop nonlinear bilateral teleoperation system is investigated by using the above control scheme when the slave robot is in contact with the environment in steady-state condition. The position error in this condition is given by

\[ q_s - q_m = \frac{F_h - F_c}{K_m} \]  
\[ q_s - q_m = \frac{F_c - F_h}{K_s} \]  

(13)  
(14)

Fig. 3 Simulation results without force signals: (a) position tracking and (b) force reflection

Fig. 4 (a) Master control input and (b) slave control input
For this condition, $F_h - F_e \to 0$. As a result, it could be concluded that during contact, in addition to force reflection, position error converges to zero as well.

For verification, a 1DOF robot simulation was carried out with the external force signals imported into the control scheme globally. The simulation results are as follows (Fig. 10).

For verification, a 1DOF robot simulation was carried out with the external force signals imported into the control scheme globally. The simulation results are as follows (Fig. 10).

Figure 10(a) shows the position tracking of the master and slave robot in free motion and when the slave robot is in contact with the environment. According to Fig. 10, it appears that when external force signals are globally imported into the control scheme, position tracking of the master and slave occurs appropriately in contact motion. Figure 10(b) shows that in this condition, force reflection is also satisfied.

In this condition, the control scheme values are shown in Fig. 11.

4 Nonlinear Bilateral Macro–Micro Teleoperation Control Design

As mentioned in Sec. 3, using external forces in the control scheme improves the bilateral teleoperation system’s transparency. In this section, a control scheme is proposed for nonlinear bilateral macro–micro teleoperation systems. The control scheme consists of estimated external forces in addition to the PD controller. There are two main problems with using such algorithms, the
first of which is the difference of scales between the master and slave robots. This problem should be mitigated by using special coefficients. The second issue is the lack of external forces; in this condition estimated external forces is utilized.

The control scheme is given by

\[
T_m = K_m \left( \frac{1}{k_p} q_m(t - T) - q_m \right) - B_m \dot{q}_m + k_l F_e + g_m
\]

(15)

\[
T_s = K_s \left[ q_s - k_p q_m(t - T) \right] + B_s q_s + \frac{1}{k_l} \dot{F}_h - g_s
\]

(16)

where \(K_m, K_s, B_m, \) and \(B_s\) are positive definite matrices in \(R^{n \times n}\); \(F_e\) and \(F_c\) are the estimated human and environmental forces; and \(k_p\) and \(k_l\) are position and force scale factors, respectively.

4.1 Force Estimation Algorithm. The difference between the estimated and actual output is the main idea behind force estimation algorithm design [22].

The nonlinear teleoperator dynamic would be written without subindices as

\[
M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + g(q) = H + F
\]

(17)

where \(M\) and \(C\) are inertia and Coriolis matrices, respectively; \(H\) is the control input and \(F\) the external force.

The following algorithm has been proposed for the estimation of external force:

\[
\dot{\hat{F}} = -L \dot{\hat{F}} + L[M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) - H]
\]

(18)

where \(\hat{F}\) and \(L\) are the external estimated force and observer gain matrix, respectively. This algorithm has the disadvantage that the acceleration signal needs to be measured. But acceleration signal measurement is not possible in many robotic tasks. Moreover, numerical differentiation of the velocity signal makes the signal too noisy. To avoid this problem, an auxiliary variable is proposed so that force signal measurement can be ruled out

\[
Z(t) = \hat{F}(t) - P(q)
\]

(19)

\[
\dot{P}(q) = LM(q)\ddot{q}
\]

(20)

where \(\alpha\) is an arbitrary positive constant. According to Eq. (20), \(P(q)\) would be as follows:

\[
P(q) = \alpha \dot{q}
\]

(21)

As a result, the necessity for an acceleration signal is eliminated. By taking the derivative from Eq. (19) and using Eq. (20), the modified force estimation algorithm is obtained as follows:

\[
\dot{Z}(t) = -LZ + L(H - C\dot{q} - g - P(q))
\]

(22)

It could be concluded that the force estimation algorithm is globally asymptotically stable [22].

This proposed force algorithm is very popular and has also been used in several previous studies [23–26]. The mentioned force estimation stability is derived for open-loop operation. In addition, estimated external forces must be transmitted to another side, and as mentioned earlier, when a signal in a teleoperation system is supposed to be transmitted to another side through communication channels a time delay is imposed on it. This delayed signal engenders adverse effects on the system’s performance as well as the force estimation algorithm. Therefore, the estimation approach must be modified for closed-loop applications and take into account the delayed signals as well.

Due to the presence of time delay in communication channels, the human force applied on the master robot and the environment force exerted on the slave robot are estimated on the slave and
master sides, respectively. This novel force estimation algorithm for the master robot is proposed as follows:

\[
F_{\text{h}}(t) = Z_{\text{h}}(t) + P_h(\dot{q}_h(t - T))
\]

\[
\dot{P}_h(\dot{q}_h(t - T)) = -L_h M_m(q_m(t - T)) \ddot{q}_m(t - T)
\]

\[
\dot{Z}_{\text{h}}(t) = -L_h Z_h + L_h(T_h(t - T) - C_m \ddot{q}_m(t - T))
\]

\[
- \dot{g}_m(t - T) - P_h(\dot{q}_h(t - T))
\]

\[
+ M_m^{-1}(q_m(t - T)) K_f \ddot{q}_m - M_m^{-1}(q_m(t - T)) \times \Delta F_h
\]

\[
+ \left( M_m^{-1}(q_m(t - T)) + \frac{K_f}{K_c} \right) \Delta F_2
\]

\[
L_h = z M_m^{-1}(q_m(t - T))
\]

where

\[
\Delta F_1 = F_h - k_f \dot{F}_h
\]

\[
\Delta F_2 = F_e - \frac{1}{k_f} \dot{F}_h
\]

The force estimation error dynamics for the human and environmental forces are simply specified by

And for the slave robot the proposed algorithm is

\[
F_{\text{e}}(t) = Z_e(t) + P_e(\dot{q}_e(t - T))
\]

\[
\dot{P}_e(\dot{q}_e(t - T)) = L_e M_s(q_s(t - T)) \ddot{q}_s(t - T)
\]

\[
\dot{Z}_{\text{e}}(t) = -L_e Z_e + L_e(T_e(t - T) - C_s \ddot{q}_s(t - T) + g_s(t - T) - P_e(\dot{q}_e(t - T)))
\]

\[
- \dot{M}_s^{-1}(q_s(t - T)) \ddot{q}_s - M_s^{-1}(q_s(t - T)) \times \Delta F_e
\]

\[
+ \left( M_s^{-1}(q_s(t - T)) + \frac{K_f}{K_s} \right) \Delta F_1
\]

\[
L_h \text{ and } L_e \text{ are the observer gains proposed by}
\]

\[
L_h = z M_m^{-1}(q_m(t - T))
\]

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Fig. 10 Simulation results with force signals: (a) position tracking and (b) force reflection

Fig. 11 (a) Master control input and (b) slave control input
\[ \Delta F_h = F_h(t-T) - \dot{F}_h = F_h(t-T) - Z_h - P_h(\dot{q}_h(t-T)) \]
\[ = F_h(t-T) - L_\alpha \Delta F_h - M_m^{-1}(q_m(t-T)k_f \frac{K_m}{K_s} \dot{q}_s - M_m^{-1}(q_m(t-T)) (1 + k_f \left[ C_m(q_m(t-T)) - ||\Delta F_h||_2^2 \right]) \Delta F_2 + M_m^{-1}(q_m(t-T)) x \Delta F_h \]

(31)

\[ \Delta F_e = F_e(t-T) - \dot{F}_e = F_e(t-T) - Z_e - P_e(\dot{q}_e(t-T)) \]
\[ = F_e(t-T) - L_\alpha \Delta F_e + M_e^{-1}(q_e(t-T)) \frac{k_e}{k_f} \dot{q}_m - M_m^{-1}(q_m(t-T)) \]
\[ \left( \frac{1}{k_f} C_e(q_e(t-T)) - ||\Delta F_e||_2^2 \right) \Delta F_1 + M_m^{-1}(q_m(t-T)) x \Delta F_e \]

(32)

Stability and convergence of the estimation error dynamics together are analyzed with the designed controller.

4.2 Stability Analysis. According to the model dynamics (1) and (2) and control laws (15) and (16), stability of the closed-loop system is considered.

A lemma and assumption are presented, which can help prove stability.

**Assumption 1.** Due to the lack of information about the rate of human and environmental forces, it is assumed that the rate of change of forces is bounded

\[ \exists \delta_m > 0 \text{ such that } ||\Delta F_h||_2 < \delta_m, \quad \forall \, t > 0 \]

(33)

\[ \exists \delta_e > 0 \text{ such that } ||\Delta F_e||_2 < \delta_e, \quad \forall \, t > 0 \]

(34)

**Lemma 1.** For any vector signals x, y and any T, x > 0, there exist

\[ 2 \int_0^T x^T(a) \left[ \int_0^T y(a-b) \, db \right] \, da \leq x||x||_2^2 + \frac{T^2}{2} ||y||_2^2 \]

(35)

where ||.||_2 is the L2-norm of the signal.

The proof of the lemma is established with the direct application of Young’s and Schwarz’s inequality.

**Theorem 1.** For stability and performance analysis of the closed-loop macro-micro teleoperation system, the non-negative candidate Lyapunov function is used

\[ V(q_i, \dot{q}_i, t, \Delta F_i) = k_p^2 \dot{q}_m^T M_m(q_m) \dot{q}_m + \frac{K_m}{2} \dot{q}_m^T M_e(q_m) \dot{q}_m \]
\[ + \frac{1}{2} \Delta F_1^T M_1(q_m(t-T)) \Delta F_1 + \frac{1}{2} \Delta F_2^T M_2(q_m(t-T)) \Delta F_2 \]
\[ + 1 \left( \Delta F_1 - k_f \Delta F_e \right)^T \left( \Delta F_2 - \frac{1}{k_f} \Delta F_h \right) \]

(36)

According to the presented Lyapunov, it could be claimed that the mentioned system is stable if the following conditions are satisfied:

\[ B_m > \frac{K_m}{2} \left( x_m + \frac{T^2}{2} \right) \]

(37)

\[ B_e > \frac{K_m}{2} \left( x_e + \frac{T^2}{2} \right) \]

\[ \forall \, t > 0 \]

**Proof.** With the derivative of the candidate Lyapunov function and substituting control laws (15) and (16), force estimation algorithms (31) and (32) and by using Property P1, the following equation is obtained:

\[ \dot{V} = -k_p^2 \dot{q}_m^T B_m \dot{q}_m - k_p^2 \dot{q}_m^T \frac{K_m}{K_s} \dot{q}_m + k_p^2 \dot{q}_m^T \left[ M_m(q_m(t-T) - q_m) \right] \]
\[ + \frac{k_p}{k_s} \dot{q}_m^T \left[ M_m(q_m(t-T) - q_m) - \Delta F_1^T M_1(q_m(t-T)) \Delta F_2 + M_m^{-1}(q_m(t-T)) x \Delta F_e \right] \]
\[ + \frac{1}{k_f} \left( \Delta F_1 - k_f \Delta F_e \right)^T \left( \Delta F_2 - \frac{1}{k_f} \Delta F_h \right) \]

(38)

There is a relation between position and velocity signals as shown in Eq. (39), which is substituted into Eq. (38) to simplify it

\[ \int_0^T \dot{q}_m(t-a) \, da = \int_0^T \frac{\partial q_m(t-a)}{\partial a} \, da = q_m(t-T) - q_m(t) \]

(39)

Therefore, it could be concluded that

\[ \dot{V} = -k_p^2 \dot{q}_m^T B_m \dot{q}_m - \frac{B_e K_m}{K_s} \dot{q}_m^2 \]
\[ + \frac{K_m}{k_s} \left[ \dot{q}_m^T \int_0^T \dot{q}_m(t-a) \, da + \frac{1}{k_f} \int_0^T \dot{q}_m(t-a) \, da \right] \]
\[ - z k_f \frac{\Delta F_1^T M_1(q_m(t-T)) \Delta F_1}{k_f} \]
\[ + \Delta F_1^T \left( \frac{1}{k_f} F_h(t-T) - \frac{1}{k_f} F_e \right) + \Delta F_2^T \left( k_f^2 F_2(t-T) - k_f F_h \right) \]
\[ - k_f \frac{\Delta F_1^T \Delta F_1}{k_f} - \frac{1}{k_f} \frac{\Delta F_2^T \Delta F_2}{k_f} \]

(40)

According to Lemma 1 and Assumption 1, a bound on the integral of V would be obtained. By integrating Eq. (40) and using Lemma 1

\[ V(t) - V(0) \leq -\left[ k_p^2 B_m - \frac{k_p K_m}{2} \left( x_m + \frac{T^2}{2} \right) \right] ||\dot{q}_m||_2^2 \]
\[ - \left[ \frac{B_e}{k_s} - \frac{k_e}{k_f} \left( x_e + \frac{T^2}{2} \right) \right] ||\dot{q}_m||_2^2 \]
\[ + \left\{ -z k_f (1 - k_f) ||\Delta F_1||_2^2 ||\Delta F_2||_2^2 - \frac{2}{k_f} \left( 1 - k_f \right) ||\Delta F_2||_2^2 ||\Delta F_2||_2^2 \right\} \]
\[ - \left( \frac{z}{k_f} k_f ||\Delta F_2||_2^2 ||\Delta F_2||_2^2 - 2 \delta ||\dot{M}_m(q_m(t-T)) + I|| (||\Delta F_2|| + ||\Delta F_h||) \right) \]
\[ \times dt - k_f ||\Delta F_1||_2^2 - \frac{1}{k_f} ||\Delta F_2||_2^2 \]

(41)
It is noted that if $B_m B_s > T^2 K_m K_s$, as a result $k_p B_m > K_m/2 (x_m + (T^2/x_s))$, $B_s > (K_m/k_p)/2 (x_s + (T^2/x_m))$. There is a positive solution for $x_m$ and $x_s$ as well. It is noticeable that $k_1$ and $k_2 \in (0, 1)$. Therefore,

$$V(t) - V(0) \leq - \left[ k_p^2 B_m - \frac{k_p K_m}{2} \left( x_m + \frac{T^2}{x_s} \right) \right] \|q_m\|^2_k$$

$$+ K_m \left[ \frac{B_s}{k_s} - \frac{k_s}{2} \left( x_s + \frac{T^2}{x_m} \right) \right] \|q_s\|^2_k$$

$$+ \int_0^t \left\{ -zk_i (1 - k_i) A F_i^2 \right\} \|q_i\|^2_k + \frac{k_i}{k_f} \|q_i\|^2_k$$

$$\left\{ |F_1|^2 |A F_1|^2 - \frac{2}{k_f} k_2 |A F_2|^2 \right\} \right\} dt$$

$$- k_i |A F_1|^2 - \frac{1}{k_f} |A F_2|^2$$

$$\left( |A F_1|^2 + |A F_2|^2 \right) > 2 \frac{\delta k_i |M_i q_i(t - T) + I|}{k_1 x_1}$$

$$\left( |A F_1|^2 + |A F_2|^2 \right) > 2 \frac{\delta k_i |M_i q_i(t - T) + I|}{k_2 x_2}$$

$$\left( |A F_1|^2 + |A F_2|^2 \right)$$

(42)

$V$ is continuously differentiable, positive definite, and radially unbounded. By means of Definition 4.2 in Ref. [27], there are class $K_\infty$ functions $x_1(\cdot)$ and $x_2(\cdot)$ such that $x_1(\cdot) \leq V \leq x_2(\cdot)$. By using Theorem 4.18 in Ref. [27], the tracking error is globally uniformly bounded.

Thus, from Eq. (42), it could be deduced that the closed-loop nonlinear bilateral macro–micro teleoperation system in the presence of time varying external forces is stable.

5 Controller Performance Analysis

5.1 Free Motion Analysis

**Theorem 2.** With regard to the proposed control scheme, position tracking would occur in free motion and the position error would converge to zero. In such case, it is assumed that the human and environmental forces equal zero ($F_h = F_e = 0$).

**Proof.** By satisfying $B_m B_s > T^2 K_m K_s$, with regard to Eq. (42) and with the non-negative of $V$, it is proven that $q_m$, $q_s$, $A F_1$, $A F_2$, $A F_3$, and $A F_4$ are $L_2$. Thus, it could be concluded that $q_m$, $q_s$, $A F_1$, $A F_2$, $A F_3$, and $k_p q_m - q_s \in L_\infty$ with regard to Eq. (36), property 2 and being bounded by the Lyapunov function.

It is demonstrated that $q_m$, $q_s$, $A F_1$, $A F_2$, $A F_3$, and $A F_4$ are uniformly continuous and will converge to zero since they belong to $L_2$.

From the external force estimation error dynamics (31)–(34), it can be concluded that $A F_3$, $A F_4$, $A F_1$, and $A F_2$ are $L_2$ together with $A F_3$, $A F_2$, $A F_3$, and $A F_4$ $L_2 \cap L_\infty$. It is proven that $A F_1$, $A F_2$, $A F_3$, and $A F_4 \to 0$.

According to

$$k_p q_m - q_i(t - T) = k_p q_m - q_s - q_i(t - T)$$

and

$$q_i(t - T) = \int_0^t q_i(t - a) \, da \leq \left( \int_0^t \left| q_i(t - a) \right|^2 \, da \right)^{1/2}$$

$$\leq T^{1/2} \|q_i\|_2$$

(44)

According to Eqs. (43) and (44) and regard to $q_s \in L_2$ and $k_p q_m - q_s \in L_\infty$, it could be deduced that $k_p q_m - q_s$ $(t - T) \in L_\infty$. By doing the same computations, it can be verified that $k_p q_m - q_s$ $(t - T) \in L_\infty$. It is clear that in Eq. (44) the Schwartz inequality was used.

The system dynamic can take the following form:

$$q_m = M^{-1}_m [K_m \left[ \frac{1}{k_p} q_s(t - T) - q_m \right] - (B_m + C_m) q_m + k_f F_e]$$

$$q_s = M^{-1}_s [-K_s (k_p q_m(t - T)) - (B_s + C_s) q_s + \frac{1}{k_f} F_h]$$

(45)

According to Eqs. (45) and (46), and Properties 2 and 3, it could be deduced that $q_m$, $q_s \in L_\infty$. It is proven that $q_m$, $q_s \to 0$, with regard to $q_m$, $q_s \in L_\infty$, and $q_m$, $q_s \in L_2 \cap L_\infty$.

It is proven that $q_m$, $q_s \to 0$, then position coordination could be investigated. Thus, $q_m$ and $q_s$ should be checked.

In investigating $q_m$ and $q_s$, the following assumption is considered:

(A1) The terms $\partial^2 M_i / \partial q_i^2 / \partial q_i^2$ are bounded.

By differentiating Eqs. (45) and (46), two terms appear which should be considered. The first one to be included is $d/dt M_{i1}$ times bounded signal. The second is the product of $M_{i1}$ times the derivative of the term in brackets. For the first term, it is specified as follows:

$$d/dt M_{i1} = -M_{i1}^{-1} M_{i1} M_{i1} = -M_{i1}^{-1} (C_i^T + C_i) M_{i1}$$

(47)

Due to Properties P2 and P3, $d/dt M_{i1}$ is bounded. According to assumption A1, the derivative of the term in brackets is also bounded. Finally, $d/dt q_m$, $d/dt q_s$ is bounded. Thus, $q_m$, $q_s$ are uniformly continuous. It could be concluded that the integral exists as follows due to the continuity of these signals.

$$\int_0^t q_i(t) \, da = q_i(t) - q_i(0)$$

(48)

By using the fact that $q_i \to 0$ and taking the limit as $t \to \infty$, it appears that $\lim_{t \to \infty} q_i(t) = -q_i(0)$, which is bounded. According to Barbalat’s Lemma, it can be claimed that $q_m$, $q_s \to 0$.

With the above findings $(q_m, q_s \to 0)$, $(q_m, q_s \to 0)$, and $(A F_1, A F_2 \to 0)$, the master and slave position coordinates are achieved by

$$\lim_{t \to \infty} [k_p q_m(t) - q_m(t - T)] = 0$$

5.2 Contact Analysis

**Theorem 3.** The condition presently considered is that the slave robot is in contact with the environment. The following assumptions can also be made for steady-state conditions:

(A2) $F_h$, $F_e \approx 0$

(A3) $q_m$, $q_s \approx 0$

(A4) $q_m$, $q_s \approx 0$

(A5) $q_m(t) = q_m(t - T), q_s(t) = q_s(t - T)$

**Proof.** Regarding Assumptions A2, A3, A4, and A5, the closed-loop nonlinear bilateral macro–micro teleoperation system is specified by

$$k_p (q_s - k_p q_m) = F_h - k_p F_e$$

$$k_s (q_s - k_p q_m) = F_e - \frac{1}{k_f} F_h$$

(49)

(50)

It has been proven that $A F_1$ and $A F_2$ converge to zero. Accordingly, it could be deduced that position error converges to zero when the slave robot is in contact with the environment in steady-state condition. Therefore, $A F_1$ and $A F_2$ converge to zero and it could be concluded that $F_h \to k_F e$. This means that in nonlinear bilateral macro–micro teleoperation systems, position error in free
motion and when the slave robot is in contact with the environment in steady-state condition converges to zero using the proposed control scheme. Force reflection occurs desirably. The main achievement of the proposed controller is that it demonstrates position error converges to zero and force reflection occurs at the same time.

The proposed control structure is shown in Fig. 12.

6 Experimental Results

The master employed is a 3DOF Haptic International Phantom Omni [28]. A 6DOF force sensor was installed on the master robot to validate the estimated human force algorithm. This force sensor is capable of measuring force in the $x$, $y$, $z$ directions and torque in the $x$, $y$, $z$ directions as well. The master and force sensors are shown in Fig. 13.

The slave robot is a 3DOF piezoelectric stage as shown in Fig. 14. This 3DOF piezoelectric actuator can move in the $x$, $y$, $z$ directions at the same time and maximum displacement of this actuator is 400 μm in every direction. In addition, a force sensor was installed on the piezoelectric actuators to measure the environment force exerted on the slave robot.

Prior to the experiments, the master and slave robots’ dynamics were identified. The dynamic models of the master and slave robots are presented in the Appendix.

6.1 Dynamic Model of Piezoelectric Actuator. For piezoelectric actuators, a second-order dynamic is utilized. The dynamic model is divided into two parts. The first part proposes a common second-order linear dynamic that refers to the mass-spring-damper system. The second part describes the hysteresis nonlinearity effect. Figure 15 shows the linear second-order dynamics of the piezoelectric actuator that would be added by the nonlinearity effect of hysteresis in the input.

The dynamic model is represented by

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = H_F(v(t))$$

(51)

where $m$, $c$, and $k$ are the mass, viscous coefficient, and stiffness, respectively; $x(t)$ and $v(t)$ represent the actuator position and input voltage respectively; and $H_F(v(t))$ expresses the hysteretic relation between the input voltage and excitation force [29].

The piezoelectric actuators have high stiffness, a situation that allows acceleration and velocity effects to be neglected. As a result, Eq. (51) is rewritten as follows:

$$x(t) = \frac{1}{k}H_F(v(t)) = H_s(v(t))\{m\ddot{x}(t) \ll c\dot{x}(t) \ll kx(t)\}$$

(52)

This equation correlates the input voltage with the actuator displacement. The advantage of this simplification is that instead of identifying the nonlinear relation of input voltage and exciting force, the nonlinear relation of input voltage and position are
identified. Therefore, the necessity for an accurate force sensor is eliminated and the position sensor of the actuator can prepare the required position signals. As a result, the dynamic actuator model is

\[ m \ddot{x}(t) + c \dot{x}(t) + k x(t) = k H_x(v(t)) \]  

Hysteresis caused by the dynamic piezoelectric actuator model is treated nonlinearly. To cope with the nonlinear effects created, it is first identified and then inserted in the dynamic model as an inverse. This effect causes the dynamic model to be treated linearly (Fig. 16)

\[ v = H^{-1}_x \left( \frac{1}{k} u(t) \right) \]

\[ m \ddot{x}(t) + c \dot{x}(t) + k x(t) = u(t) \]

The hysteresis model is identified using the Prandtl–Ishlinskii (PI) model [29].

A generalized Prandtl–Ishlinskii model is used for both hysteresis identification and compensation. The most important advantage of this model is its simplicity and that its inverse could be calculated analytically. In addition, this approach can be utilized in open-loop systems where the feedback of signals is not accessible. A rate-independent backlash operator is the primary operator in the PI hysteresis model, as shown in Fig. 17.

This operator is defined as follows:

\[ y(t) = w_h H_r[x, y_0](t) \]

\[ H_r = \max [x(t) - r, \min \{x(t) + r, y(t - T)\}] \]

\[ y(0) = \max [x(0) - r, \min \{x(0) + r, y_0\}] \]

\[ w_h = \sum_{j=0}^{i} w_{hj} \]

Fig. 16  Inverse feedforward compensation of hysteresis effect

Fig. 17  Backlash operator with threshold \( r \) and weighting value \( w_h \)

Fig. 18  Summation of backlash operators

Fig. 18  Summation of backlash operators
where x is the control input, y is the actuator response, r is the control input threshold value or the magnitude of backlash, and T is the sampling period. The initial consistency condition \( y(0) \) is usually but not necessarily initialized to zero.

The Prandtl–Ishlinskii method expresses that the hysteresis loop could be identified as the summation of a number of backlash operators with different thresholds \((r)\) and weights \((w_h)\)

\[
y(t) = \sum_{n=0}^{\infty} w_n H^r_n[x, y_0](t)
\]

The summation of backlash operators is shown in Fig. 18.

The key idea of an inverse feedforward compensation of hysteresis is to cascade the inverse hysteresis operator \(H^{-1} \) with the actual hysteresis. As a result, an identity mapping between the desired actuator output \(x_d(t)\) and actuator response \(x(t)\) would be obtained. The structure of inverse feedforward hysteresis compensation is shown in Fig. 19.

As seen in Fig. 19, the inverse PI operator \(H^{-1} \) uses \(x_d(t)\) as an input and transforms it into a control input \(v = H^{-1}(x_d)\) which produces \(x(t)\) in the hysteretic system that closely tracks \(x_d(t)\).

As a result, the feedforward positioning of the actuator for low frequency trajectories is achieved as follows:

\[
x(t) = H_k[H^{-1}_k[x_d(t)]]
\]

### 6.2 Controller Performance Analysis

The experimental setup is shown in Fig. 20. Two force sensors were used on the master and slave robots to validate and compare the real and estimated forces. To capture data, a DS1104 dSPACE data acquisition and controller board was utilized. MATLAB/SIMULINK was applied to implement the control scheme. For controller implementation and communication channel sampling, the time interval was set at 0.001 s. In addition, there is a block in MATLAB/SIMULINK, based on which a time delay between communication channels can be generated. The value of the time delay considered in this research is 0.3 s.

There are two points worth noting:

1. Regarding the master and slave robot dynamics, signals from the master robot transmitted to the slave robot should be scaled down while signals from the slave robot sent to the master robot should be scaled up.
2. The position tracking of the master and slave robots is considered in 2DOF. A validation and force estimation algorithm is considered to have 1DOF.

The control gains along with the scale factors and coefficient of the estimated external forces used in the experiment are as follows (Tables 3 and 4).

In the experiment, the first condition considered is that the estimated forces are not imported into the control scheme. The results are shown in Fig. 21. It is noticeable that the time delays in the communication channels from master to slave and vice versa are considered equal \((T_1 = T_2 = 0.3 \text{ s})\).

Figures 21(a) and 21(b) show the position tracking of the master and slave robot and human and environmental forces, respectively. According to Fig. 21, it can be deduced that the control scheme with no estimated external forces performs well in free motion. It can also be seen that contact occurs between the 12 and 32 s periods. In this condition, position tracking deteriorates. The main problem with using this control scheme is the existence of position error during contact. In this circumstance, force reflection occurs appropriately. It is observed that in free motion, due to the presence of delay between communication channels, a force is exerted on the master robot. The value of human and environmental forces is proportional to the position error. It is also evident that the position error value in this condition is 0.08 rad.

Figures 22(a) and 22(b) present position tracking as well as human and environmental forces, respectively. The contact area is also specified in Fig. 22. The slave robot is in contact with the environment between 10 and 30 s. Figure 22(a) indicates that
Position tracking in free motion occurs correctly. It also shows that position error converges to zero during contact condition. Figure 22(b) illustrates that human force follows environmental force efficiently when estimated external forces are imported into the control scheme.

Position tracking in other DOF of the master and slave robot is depicted in Fig. 23. In this condition, there is no hard environment against the slave robot.

As seen in Fig. 23, it could be concluded that in other DOF, position error converges to zero in the presence of estimated external forces.

The results signify that the estimated human force converges to the estimated environmental force appropriately. This means that estimated forces in the control structure would considerably improve the transparency of the teleoperated system.

However, the accuracy of the force estimation method should be investigated. The load cells utilized on the master and slave robots validate the accuracy of the force estimation approach (Fig. 24).

It is clear that the estimated forces converge to real forces appropriately.

7 Conclusion

A PD controller with a force estimation algorithm for a nonlinear bilateral macro–micro teleoperation system was designed. First, the PD controller was analyzed, and then a solution for improving the transparency of the macro–micro teleoperation system when the slave robot collides with the environment was proposed. A force estimation algorithm was developed for time-variant human and environmental forces. Thus, by using an appropriate candidate Lyapunov function, it was proven that the closed-loop bilateral macro–micro teleoperation is stable. It could also be deduced that in the presence of a control scheme, position error converges to zero in free motion and when the slave robot is in collision with the environment. Furthermore, it was also shown that force reflection occurs during contact.

The most important achievement in this paper is the investigation of the stability and transparency of the macro–micro...
telemotion system in the presence of estimated forces and without requiring force sensors. Excellent tracking and force reflection take place in the case when the slave robot is in contact with the environment. Finally, the experimental results verify the effectiveness of the designed control scheme.

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Appendix

A1 Dynamic Model of the Master Robot (Phantom Omni Haptic Device)

\[
M(\dot{\theta}) \ddot{\theta} + C(\theta, \dot{\theta}) \dot{\theta} + N(\theta) = \tau
\]

\[
M(\theta) = \begin{bmatrix}
    m_{1,1} & m_{1,2} & m_{1,3} \\
    m_{2,1} & m_{2,2} & m_{2,3} \\
    m_{3,1} & m_{3,2} & m_{3,3}
\end{bmatrix}
\]

\[
m_{1,1} = p_1 + p_2 \cos(2\theta_2) + p_3 \cos(2\theta_1) + p_4 \cos(\theta_2) \sin(\theta_3)
\]

\[
m_{1,2} = p_5 \sin(\theta_2)
\]

\[
m_{1,3} = 0
\]

\[
m_{2,1} = p_5 \sin(\theta_2)
\]

\[
m_{2,2} = p_6
\]

\[
m_{2,3} = -0.5p_4 \sin(\theta_2 - \theta_3)
\]

\[
m_{3,1} = 0
\]

\[
m_{3,2} = -0.5p_4 \sin(\theta_2 - \theta_3)
\]

\[
m_{3,3} = 0
\]

\[
C(\theta, \dot{\theta}) = \begin{bmatrix}
    c_{1,1} & c_{1,2} & c_{1,3} \\
    c_{2,1} & c_{2,2} & c_{2,3} \\
    c_{3,1} & c_{3,2} & c_{3,3}
\end{bmatrix}
\]

\[
c_{1,1} = -2p_2 \dot{\theta}_2 \sin(2\theta_2) - 2p_3 \dot{\theta}_1 \sin(2\theta_1) + p_4 \dot{\theta}_3 \cos(\theta_2) \cos(\theta_3)
\]

\[
c_{1,2} = p_5 \dot{\theta}_2 \cos(\theta_2)
\]

\[
c_{1,3} = 0
\]

\[
c_{2,1} = 2p_2 \dot{\theta}_1 \cos(\theta_2) \sin(\theta_2) - 0.5p_4 \dot{\theta}_1 \sin(\theta_2) \sin(\theta_3)
\]

\[
c_{2,2} = 0
\]

\[
c_{2,3} = 0.5p_4 \dot{\theta}_1 \cos(\theta_2 - \theta_3)
\]

\[
c_{3,1} = 2p_2 \dot{\theta}_1 \cos(\theta_2) \sin(\theta_2) - 0.5p_4 \dot{\theta}_1 \cos(\theta_2) \cos(\theta_3)
\]

\[
c_{3,2} = -0.5p_4 \dot{\theta}_2 \cos(\theta_2 - \theta_3)
\]

\[
c_{3,3} = 0
\]

\[
N(\theta) = \begin{bmatrix}
    n_1 \\
    n_2 \\
    n_3
\end{bmatrix}
\]

\[
n_1 = 0
\]

\[
n_2 = p_4 \cos(\theta_2) + \theta_2 - 0.5\pi
\]

\[
n_3 = p_5
\]

\[
\tau = \begin{bmatrix}
    T_1 \\
    T_2 \\
    T_3
\end{bmatrix}
\]

A2 Dynamic Model of the Slave Robot (Piezoelectric Actuator Device)

\[
x(t) + c_1(t) + kx(t) = \tau
\]

\[
M(x) = \begin{bmatrix}
    0.2 & 0 & 0 \\
    0 & 0.2 & 0 \\
    0 & 0 & 0.2
\end{bmatrix}
\]

\[
C(x, s) = \begin{bmatrix}
    0.003 & 0 & 0 \\
    0 & 0.003 & 0 \\
    0 & 0 & 0.003
\end{bmatrix}
\]

\[
K(x) = \begin{bmatrix}
    7 \times 10^{-4} & 0 & 0 \\
    0 & 7 \times 10^{-4} & 0 \\
    0 & 0 & 1.5 \times 10^{-5}
\end{bmatrix}
\]

References


