Passivity and RISE based Robust Control for Bilateral Teleoperation System with Communication Delay

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Abstract—In this paper, a method for passivity- and robust integral of the sign of the error (RISE)-based control of a nonlinear teleoperation system with communication delays is proposed. This control strategy can accurately achieve coordinate positioning under conditions with viscous friction and unmodeled effects compensation errors, and its stability condition is independent of robot model parameter uncertainties and time delay. Using passivity-based stability analysis, the stability and tracking performance of this system are demonstrated, and experimental trials are performed to verify its effectiveness.

I. INTRODUCTION

Teleoperation systems, which extend human sensing and manipulation capability to remote locations, consist of a dual-robot system in which a remote slave robot tracks the motions of a master robot directly controlled by a human operator. In particular, feedback from the slave to the master representing contact information can be used to provide a more extensive sense of telepresence: this process is called “bilaterally-controlled teleoperation” [1].

In bilateral teleoperation, the master and slave manipulators are coupled via a communication network, and a time delay occurs in the transmission of data back and forth between the master and slave sites. As delays in this closed-transfer loop may destabilize an otherwise stable system, one objective in designing a bilateral teleoperation system is to ensure its robustness against such delays in the communication channel. A literature survey [1], [2] shows that various schemes have been developed to analyze and ensure stability in bilateral teleoperation. These include the use of a passivity-based scattering transformation.

Anderson et al. [3] proposed a method for maintaining the stability of a teleoperating system with constant delays, while Chopra et al. [4], Namerikawa et al. [5], and Kawai and Namerikawa et al. [6] have proposed the use of additional control terms with position feedforward/feedback elements to improve position coordination and enforce reflection performance.

Proportional (P-) and proportional-derivative (PD-)-type controllers without scattering transformation have been proposed in order to guarantee stability under constant or time varying communication delay [7], [8], [9], [10], [11], [12]. Using such controllers, position coordination and force reflection can be achieved through explicit feedforward/feedback control. However, to obtain accurate position coordination it is necessary to compensate for the influence of gravity or friction, and because precise model parameters relating to the dynamics of friction may not be available or may slowly change over time, accurately compensating these effects can be challenging.

Motivated to improve design robustness, Ortega et al. [13] and Alvarez et al. [14] developed a proportional-integral-derivative (PID) controller that can guarantee stability regarding the influence of gravity or friction. Kawai and Namerikawa [15] have proposed a passivity-based PID-type controller to improve tracking performance with communication delay. Utilizing a PID with integral sliding mode control, Dixon et al. [16], [17] developed a robust-integral-of-the-sign-of-the-error (RISE) control system useful with a human limb having nonlinear, uncertain muscle control with nonvanishing additive disturbances. Although RISE methods have been shown to be useful in effecting control with robustness and high positioning accuracy, a PID-based RISE controller of a teleoperation system with time delays has not yet been evaluated, owing to challenges related to stability analysis.

In this paper, a robust passivity- and RISE-based controller for nonlinear teleoperation systems with communication delay is presented. In this method, master and slave robots are passively controlled by feedback systems based on outputs such as position and velocity signals. A new control law is designed for generating outputs from a PI controller that is equivalent to using a PID controller with respect to robot joint angles. We expect that this control strategy can be used to achieve robust and accurate position coordination even in conditions with viscous friction and unmodeled effects compensation errors with a stability condition that is independent of robot model parameter uncertainties and the magnitude of time delay. After demonstrating the stability and tracking performance of this proposed RISE-controlled teleoperation system, we experimentally verify its effectiveness.

The paper is organized as follows. In Section 2, the dynamics of a nonlinear teleoperation system and its control objectives are presented. Section 3 gives a description of a robust passivity- and RISE-based controller design, while in Section 4 the stability of the overall teleoperation system is assessed. Experimental results are presented in Sections 5, and concluding remarks are provided in Section 6.

II. TELEOPERATION SYSTEMS

For a pair of nonlinear robotic systems coupled via a communication line with a known, arbitrarily constant communication time delay, if friction and other disturbances are
regarded, then the Euler-Lagrange equations of motion for an n-link master and slave robot pair can be given as
\[
\begin{align*}
M_m(q_m) \ddot{q}_m + C_m(q_m, \dot{q}_m) \dot{q}_m + \tau_{dm} &= \tau_m + F_{op}, \\
M_s(q_s) \ddot{q}_s + C_s(q_s, \dot{q}_s) \dot{q}_s + \tau_{ds} &= \tau_s - F_{env},
\end{align*}
\]
(1)
where the subscripts "m" and "s" denote the master and the slave indices, respectively; \(q_m, \dot{q}_m, \ddot{q}_m \in \mathbb{R}^{n \times 1}\) are the joint angle vectors; \(\dot{q}_m, \ddot{q}_m \in \mathbb{R}^{n \times 1}\) are the joint velocity vectors; \(\tau_m, \tau_s \in \mathbb{R}^{n \times 1}\) are the applied torques; \(\tau_{dm}, \tau_{ds} \in \mathbb{R}^{n \times 1}\) are the disturbances (e.g., viscous friction and unmodeled effects); \(F_{op} \in \mathbb{R}^{n \times 1}\) is the operator for the force vector applied to the master by the human operator; \(F_{env} \in \mathbb{R}^{n \times 1}\) is the environmental force vector acting on the slave robot upon contact with the environment; \(M_m, M_s \in \mathbb{R}^{n \times n}\) are the inertia matrices; \(C_m(q_m), C_s(q_s) \in \mathbb{R}^{n \times 1}\) are the centripetal and Coriolis torques, respectively. The fundamental properties of master and slave robots [16], [18] used in the subsequent stability analysis are provided below.

**Property 1:** The inertia matrices \(M_i(q_i) (i = m, s)\) are symmetric positive definite matrices that satisfy
\[
\lambda_m I \leq M_i(q_i) \leq \lambda_M I,
\]
where \(\lambda_m (\lambda_M < \infty)\) denotes the strictly positive minimum (maximum) eigenvalue of \(M_i\) for all configurations \(q_i\).

**Property 2:** Under an appropriate definition of the matrix \(C_i\), the matrix \(C_i - 2\Lambda_i\) is skew-symmetric.

**Property 3:** The Coriolis and centrifugal terms \(C_i(q_i, \dot{q}_i) \dot{q}_i\) satisfy
\[
\|C_i(q_i, \dot{q}_i) \dot{q}_i\| \leq c_0 \|\dot{q}_i\|^2,
\]
for some bounded constant \(c_0 > 0\).

The following assumptions can be made for the human operator and the remote environment [4].

**Assumption 1:** The human operator and the remote environment can both be modeled as passive systems.

Under the above Assumption 1, the human operator is described as
\[
\int_0^t -F_{op}^T(\xi)r_m(\xi) d\xi \geq 0,
\]
while the remote environment is described as
\[
\int_0^t F_{env}^T(\xi)r_s(\xi) d\xi \geq 0,
\]
where \(r_m, r_s \in \mathbb{R}^{n \times 1}\) are the input vectors to the operator and the environment, respectively.

**Assumption 2:** The operator and environmental forces are bounded by functions in \(r_m\) and \(r_s\), respectively.

In this paper known, constant time delays are considered; it is assumed that both the signals transmitted to the slave from the master and vice versa are delayed by \(T_s \geq 0 \in \mathbb{R}\).

**Remark 2.1:** For simplicity and without loss of generality, we assume that the time delays over both communication paths have the same magnitude \(T_s\).

To facilitate subsequent analysis, we also make the following assumptions.

**Assumption 3:** All signals belong to \(L_{2\varepsilon}\) (i.e., to the extended \(L_2\) space).

**Assumption 4:** The velocities \(\dot{q}_m\) and \(\dot{q}_s\) equal zero for \(t < 0\).

**Assumption 5:** The disturbance term and its first derivative are bounded (i.e., \(\tau_{dm}, \tau_{ds}, \dot{\tau}_{dm}, \dot{\tau}_{ds} \in L_\infty\)).

Next, the main objectives are given as follows.

**Control Objective 1:** A teleoperation system with communication time delay will be stable in terms of \(q_m, q_s \in L_\infty\).

**Control Objective 2:** Synchronization of the teleoperation system can be achieved as described by
\[
\begin{align*}
\epsilon_{m1}(t) &:= q_s(t - T_s) - q_m(t) \rightarrow 0 \text{ as } t \to \infty, \\
\epsilon_{s1}(t) &:= q_m(t - T_s) - q_s(t) \rightarrow 0 \text{ as } t \to \infty.
\end{align*}
\]
(6)

**Control Objective 3:** In the steady state \((\dot{q}_s = \ddot{q}_s = 0)\), the static contact force on the slave will be accurately transmitted to the master and thus the human operator is described by
\[
F_{op} = F_{env}.
\]
(7)

III. CONTROL SYSTEM DESIGN

A. Feedback Passivation

The master and slave inputs can be defined using
\[
\begin{align*}
\tau_m(t) &= -M_m \dot{q}_m(t) - C_m(q_m, \dot{q}_m) + F_m(t),
\end{align*}
\]
(8)
where \(\Lambda = \text{diag}(\lambda_1, \cdots, \lambda_n) \in \mathbb{R}^{n \times n}\) is a positive definite diagonal control gain matrix, and \(F_m\) and \(F_s\) are additional inputs required for synchronized control, as described in the next subsection. Substituting (8) into (1), the master and slave robot dynamics can be represented by
\[
\begin{align*}
M_m \ddot{r}_m(t) + C_m \dot{r}_m(t) + \tau_{dm} &= F_{op} + F_m, \\
M_s \ddot{r}_s(t) + C_s \dot{r}_s(t) + \tau_{ds} &= -F_{env} + F_s,
\end{align*}
\]
(9)
where the vectors \(r_m\) and \(r_s\) are the new states of the master and slave robot, respectively, which can be defined by linear combinations of the joint angle and the joint velocity vectors as [19]
\[
\begin{align*}
\dot{r}_m(t) &= \dot{q}_m(t) + \Lambda \dot{q}_m(t), \\
\ddot{r}_s(t) &= \ddot{q}_s(t) + \Lambda \ddot{q}_s(t).
\end{align*}
\]
(10)

**Lemma 1:** In the systems described by (9), the inputs and outputs of the master and slave robot dynamics are defined as \(F_m = F_m + F_{op} - \tau_{dm}\) and \(F_s = F_s - F_{env} - \tau_{ds}\) and as \(r_m\) and \(r_s\), respectively. The systems having the above inputs and outputs will then be passive if there is a constant \(\gamma\) such that
\[
\int_0^t r_i^T(\xi)F_i(\xi) d\xi \geq -\gamma, \quad i = m, s.
\]
(11)

**Proof:** Define a positive semi-definite storage function \(V_i\) as
\[
V_i(r_i(t)) = \frac{1}{2} r_i^T(t)M_i(q_i)r_i(t), \quad i = m, s.
\]
(12)
Differentiating $V_i$ along trajectories of (9) and using Property 2, we obtain
\[
\dot{V}_i(r_i(t)) = r_i^T(t) (F'_i(t) - C_i(t)r_i(t)) + \frac{1}{2} r_i^T(t) M_i(t) r_i(t)
\]
\[
= r_i^T(t) F'_i(t).
\]  
(13)

Integrating the above equation over $[0, t]$ yields
\[
\int_0^t \dot{V}_i(r_i(\xi))d\xi = \int_0^t r_i^T(\xi) F'_i(\xi) = V_i(r_i(t)) - V_i(r_i(0))
\]
\[
\geq -V_i(r_i(0)) = -\gamma.
\]  
(14)

Hence, the dynamics are passive with respect to the input-output pair $(F'_i, r_i)$.

Using the feedback passivation dynamics in (8), the master and slave robot dynamics will be passive with respect to the new outputs (10), which contain both the joint angle and velocity vectors; thus, teleoperation can be controlled within this passivity framework for obtaining joint angle and velocity signals from new outputs.

**B. RISE Control Law**

A positive semi-definite function based on the function (12) is considered [20]
\[
V'_i(r_i(t)) = \frac{1}{2} r_i^T M_i r_i + \frac{1}{2} (\nu_i - \tau_{di})^T (\nu_i - \tau_{di}),
\]
\( i = m, s, \)  
(15)

where $\nu_i$ is assumed to be close to a estimation in order to reject $\tau_{di}$. Differentiating $V'_i$ along trajectories of (9) by using the additional input $F_i = -r_i + \nu_i$
\[
\dot{V}'_i \leq r_i^T (r_i + \nu_i - \tau_{di}) + (\nu_i - \tau_{di})^T (\nu_i - \tau_{di})
\]
\[
= -r_i^T r_i + r_i^T (\nu_i - \tau_{di}) + (\nu_i - \tau_{di})^T (\nu_i - \tau_{di}).
\]  
(16)

If the disturbance $\tau_{di}$ is a constant ($\dot{\tau}_{di} = 0$), then the input $\nu_i$ should be designed as $\dot{\nu}_i = -r_i$. However, the first derivative of the disturbance $\tau_i$ is bounded from Assumption 5,
\[
\|\dot{\tau}_{di}\| \leq \beta, \quad \beta > 0,
\]
(17)

the input $\nu_i$ needs a compensation term for the derivative of the disturbance. By using the input $\nu_i$ satisfying $\dot{\nu}_i = -r_i + \beta \text{sgn}(-r_i)$, Eq. (16) is derived as follows
\[
\dot{V}'_i \leq -r_i^T r_i + (\nu_i - \tau_{di})^T (\beta \text{sgn}(-r_i) - \dot{\tau}_{di})
\]
\[
\leq -r_i^T r_i + (\beta + |\dot{\tau}_{di}|) \int_0^t (-r_i + \beta + |\dot{\tau}_{di}|)dt.
\]  
(18)

Therefore, $\beta \text{sgn}(-r_i)$ is useful to decrease the influence by the derivative of the disturbance $\dot{\tau}_{di}$.

From the above results, the proposed control structure corresponding to (9) is shown in Fig. 1. Here, we propose the following RISE-control law
\[
\begin{align*}
F_m &= K_P \{r_s(t - T_s) - r_m\} + \nu_m, \\
\dot{\nu}_m &= K_I \{r_s(t - T_s) - r_m\} + \beta \text{sgn}(r_s - r_m), \\
F_s &= K_P \{r_m(t - T_s) - r_s\} + \nu_s, \\
\dot{\nu}_s &= K_I \{r_m(t - T_s) - r_s\} + \beta \text{sgn}(r_m - r_s) \int_0^\xi (\nu_i - \tau_{di})d\xi,
\end{align*}
\]  
(19)

where $K_P$ and $K_I$ $\in \mathbb{R}^{n \times n}$ are positive definite diagonal control gain matrices, and $\beta \in \mathbb{R}$ is the positive definite gain. Using the errors $e_{m2}$ and $e_{s2}$ defined as
\[
\begin{align*}
e_{m2} &= \dot{e}_{m1} + \Lambda e_{m1} = r_s(t - T_s) - r_m(t), \\
e_{s2} &= \dot{e}_{s1} + \Lambda e_{s1} = r_m(t - T_s) - r_s(t).
\end{align*}
\]  
(20)

The control law (19) can be rewritten once more as
\[
\begin{align*}
F_m &= K_P e_{m2} + \nu_m, \\
\dot{\nu}_m &= K_I e_{m2} + \beta \text{sgn}(e_{m2}), \\
F_s &= K_P e_{s2} + \nu_s, \\
\dot{\nu}_s &= K_I e_{s2} + \beta \text{sgn}(e_{s2}).
\end{align*}
\]  
(21)

**Remark 3.1:** The proposed control laws (21) can be rewritten as follows, in terms of the rules in (10),
\[
\begin{align*}
F_i &= K_P \{\dot{q}_i(t - T_s) - \dot{q}_i\} \\
\dot{q}_i &= D control \quad + K_P \Lambda \{q_j(t - T_s) - q_i\} + K_I \int_0^t \{\dot{q}_j(\xi - T_s) - \dot{q}_i(\xi)\}d\xi \\
\dot{q}_s &= P control \quad + K_I \Lambda \int_0^t \{\dot{q}_j(\xi - T_s) - \dot{q}_i(\xi)\}d\xi, \\
\dot{q}_s &= I control \quad + \int_0^t \beta \text{sgn}(\dot{q}_j(\xi - T_s) - \dot{q}_i(\xi))d\xi, \\
\dot{q}_s &= \text{Integral sliding mode control} \\
\dot{q}_s &= \text{Integral sliding mode control} \\
\dot{q}_s &= \text{Integral sliding mode control} \\
\end{align*}
\]  
(22)

The proposed RISE-control laws (19) can be seen as PID controllers. The P control term consists of the positions and integral of velocities, however, the velocity signals have a lot of noises in general. Thus, the controller’s parameter $K_I$ should be designed in view of the influence of P control.

These proposed RISE-control laws can be used by a PI controller with an integral sliding mode to obtain a new output $r_m$, $r_s$ and can be substituted into the feedback passivation dynamics relations in (9) to obtain a closed-loop system that can be described as
\[
\begin{align*}
M_m \dot{r}_m + C_m r_m &= F_{op} + K_P e_{m2} + \nu_m, \\
\dot{\nu}_m &= K_I e_{m2} + \beta \text{sgn}(e_{m2}), \\
M_s \dot{r}_s + C_s r_s &= -F_{env} + K_P e_{s2} + \nu_s, \\
\dot{\nu}_s &= K_I e_{s2} + \beta \text{sgn}(e_{s2}).
\end{align*}
\]  
(23)
IV. STABILITY ANALYSIS

In this section, stability analysis of a teleoperation system implementing RISE controllers is described.

A. Passivity of RISE Controller

Using the following lemma, we can analyze the passivity of the proposed RISE controllers.

**Lemma 2:** The proposed RISE controllers are passive.

**Proof:** First, define a positive semi-definite function

\[ V_{cont1i} = \frac{1}{2} e_{i2}^T K_p e_{i2} + \int_0^t e_{i2}^T K_1 e_{i2} d\xi \]

The time derivative of \( V_{cont1i} \) is given by

\[ \dot{V}_{cont1i} = e_{i2}^T K_p \dot{e}_{i2} + e_{i2}^T K_1 e_{i2} + e_{i2}^T \beta \text{sgn}(e_{i2}) \]

Integrating the above equation over \([0, t]\), the following equation is obtained

\[ V_{cont1i}(t) - V_{cont1i}(0) = \int_0^t e_{i2}^T F_i d\xi. \]  

Thus, the system is passive in terms of the error \( e_{i2} \) and the derivative of the input \( F_i \).

It is known that a integral function is passive. Thus, the system is passive in terms of the error \( e_{i2} \) and the derivative of the input \( F_i \).

The proposed RISE controller is therefore passive, as the above equations satisfy the definition of passivity shown in Fig. 2.

![Fig. 2. Block diagram of RISE controller.](image)

B. Passivity of Robot and External force

In this subsection, we analyze the passivity of robot and external forces.

**Lemma 3:** The external force and feedback passivation dynamics subsystems are passive.

**Proof:** From Lemma 1, the feedback passivation robot dynamics in (9) are passive with respect to the input/output pairs \((F_{op} + F_m - \tau_{dm}, r_m)\), \((-F_{env} + F_s - \tau_{ds}, r_s)\). Moreover, from Assumption 1 the human operator and remote environment are also passive systems. Because the robot and external force are feedback-connected to these passive systems, as shown Fig. 3, we can conclude that the external force and feedback passivation dynamics subsystems are passive.

![Fig. 3. Feedback connection of passive systems.](image)

As a closed-loop system connected via feedback to two passive systems is itself passive, the proposed teleoperation system can be described as two passive blocks \( \Sigma_{m,RC} \) and \( \Sigma_{s,RC} \), as shown in Fig. 4. \( \Sigma_{m,RC} \) is passive with respect to the input/output pair \((r_s(t - T_s) - r_m, r_m)\) and \( \Sigma_{s,RC} \) is passive with respect to the input/output pair \((r_m(t - T_m) - r_s, r_s)\).

C. Main Results

Based on the results developed above, the following theorem demonstrating that Control Objective 1 is achieved can be obtained.

**Theorem 1:** Under Assumptions 1-3, the proposed teleoperation system using a RISE controller described by (23) is stable in terms of delay independence in \( q_m, q_s \in \mathcal{L}_\infty \).

**Proof:** For two passive subsystems \( \Sigma_{m,RC} \) and \( \Sigma_{s,RC} \) the respective functions \( V_{m,RC}, V_{s,RC} \) can be defined as

\[ \dot{V}_{m,RC} = r_m^T e_{m2} = r_m^T \{r_s(t - T_s) - r_m\}, \]

\[ \dot{V}_{s,RC} = r_s^T e_{s2} = r_s^T \{r_m(t - T_m) - r_s\}. \]

Integrating (27) and (28) yield

\[ \|r_m\|_2^2 \leq \|r_s(t - T_s)\|_2^2 + 2V_{m,RC}(0), \]

\[ \|r_s\|_2^2 \leq \|r_m(t - T_m)\|_2^2 + 2V_{s,RC}(0), \]

where \( \| \cdot \|_2 \) denotes the \( \mathcal{L}_2 \) norm. Therefore, the \( \mathcal{L}_2 \)-gains of the master and slave subsystems are both less than or equal to 1. Based on the relation of (10) between \( r_m, r_s \) and \( \dot{q}_m, \dot{q}_s \) and the fact that \( r_m, r_s \in \mathcal{L}_\infty \), and outputs of the system will have the property that \( \dot{q}_m, \dot{q}_m, \dot{q}_s \) and \( \dot{q}_s \in \mathcal{L}_\infty \). Consequently, the teleoperation system is stable in terms of its delay independence. For details, see Theorem 1 of [15].

The proposition that Control Objective 2 is achieved can be obtained as follows.

**Proposition 4:** For a proposed teleoperation system described by (23). Synchronization of teleoperation can be
achieved using
\[
\begin{align*}
  e_{m1} &= q_m(t - T_s) - q_s \to 0, \\
  e_{s1} &= q_s(t - T_s) - q_m \to 0, \quad \text{as} \quad t \to \infty.
\end{align*}
\] (31)

Proof: See Proposition 4 of [15].

Remark 4.1: In the steady state \( \dot{q}_i = q_i = 0 \), the force error \( F_{op} - F_{env} \) satisfies the following equation
\[
F_{op} - F_{env} = K_P \int_0^t \{ r_s - r_s(\xi - T_s) + r_m - r_m(\xi - T_s) \} d\xi
- \beta \int_0^t \{ \text{sgn}(r_s(\xi - T_s) - r_m) - \text{sgn}(r_m(\xi - T_s) - r_s) \} d\xi. \tag{32}
\]

Although the above equation is inconsistent with Control Objective 3, it is apparent that the right-hand side of (32) becomes small for small time delays, allowing for suitable static contact force reflection in this case.

V. Evaluation by Control Experiments

In this section, we describe the experimental verification of the efficacy of the proposed teleoperation method. Experiments were carried out on a pair of linked identical direct-drive, dual-planar, revolute-joint robots, as shown in Fig. 5, where \( q_m, q_s, F_{op}, \) and \( F_{env} \) are defined as
\[
\begin{align*}
  q_m &= \begin{bmatrix} q_{m1} \\ q_{m2} \end{bmatrix}, \\
  q_s &= \begin{bmatrix} q_{s1} \\ q_{s2} \end{bmatrix}, \\
  F_{op} &= \begin{bmatrix} F_{op1} \\ F_{op2} \end{bmatrix}, \\
  F_{env} &= \begin{bmatrix} F_{env1} \\ F_{env2} \end{bmatrix}.
\end{align*}
\]

The remote environment was a hard aluminum wall that was covered by a hard rubber surface on the slave side. The operational and environmental torque (i.e., \( F_{op} \) and \( F_{env} \), respectively, in (1)) were measured using force sensors. To implement the controllers and the communication line, we used a dSPACE system (dSPACE Inc.) with a sampling rate of 2.5 [ms] and a communication time delay \( T_s \) set to 200 [ms].

To demonstrate the characteristics of the proposed system, experiments were carried to assess both the proposed RISE controller and the PID teleoperation systems. The controller parameters were set as follows, where \( K_P, K_I, \) and \( \Lambda \) all had the same value.

- **RISE**
  \[
  K_P = \begin{bmatrix} 2.5 & 0 \\ 0 & 1.3 \end{bmatrix}, \\
  K_I = \begin{bmatrix} 1.0 & 0 \\ 0 & 0.5 \end{bmatrix}, \\
  \Lambda = \begin{bmatrix} 5.7 & 0 \\ 0 & 4.9 \end{bmatrix}, \quad \beta = 0.8,
\]

- **PID**
  \[
  K_P = \begin{bmatrix} 2.5 & 0 \\ 0 & 1.3 \end{bmatrix}, \\
  K_I = \begin{bmatrix} 1.0 & 0 \\ 0 & 0.5 \end{bmatrix}, \\
  \Lambda = \begin{bmatrix} 5.7 & 0 \\ 0 & 4.9 \end{bmatrix}.
\]

Two experimental condition variants were considered
- Case 1: The slave moves without any contact.
- Case 2: The slave moves in contact with environments.

Fig. 6 illustrates the time response of \( q_m, q_s, F_{op}, \) and \( F_{env} \) in Case 2, where (a) and (b) show the results for the proposed PID and RISE controllers, respectively, from which it can be seen that both are stable, and that the controller demonstrates good tracking performance.

Figs. 7 and 8 illustrate the time response of \( q_m, q_s, F_{op}, \) and \( F_{env} \) in Case 2, where (a) and (b) indicates the results from the proposed PID and RISE controllers, respectively. In Fig. 7, the solid and dashed lines represent the master and slave, respectively; as in Case 1, the proposed system is also stable under slave contact with the remote environment. Tracking error transiently increases following slave-environment contact; however, the proposed RISE control can still track desired trajectories in this case, better than the PID control. As tracking error accumulates as an integral term of the controller during slave contact with the environment, the tracking master position is delayed, but in the steady state, after 20 [s], the position error converges with zero.

The solid and dashed lines in Fig. 8 represent \( F_{op} \) and \( F_{env} \), respectively. \( F_{env} \) is delayed in comparison with \( F_{op} \) because of the time needed to make contact with the environment. As explained in Remark 4.1, \( F_{op} \) differs from \( F_{env} \) in the steady state.
Fig. 7. Experimental results of case 2

Fig. 8. Experimental results of case 2

VI. CONCLUSIONS

In this paper, a robust passivity- and RISE-based control for a nonlinear teleoperation system with communication delay was proposed and analyzed. After showing that the master and slave robots are passive under feedback control with respect to new outputs such as position and velocity signals, we designed a control law for new outputs of a PI controller with a sliding mode. The proposed RISE-control strategy should be able to achieve accurate position coordination under viscous friction and unmodeled effects compensation errors, and we showed that its stability condition is independent of viscous friction and unmodeled effects and magnitude of time delay. The stability and tracking performance of the proposed RISE-control teleoperation system were demonstrated via passivity-based stability analysis, and its effectiveness was verified in the results of a series of experimental evaluations.

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