2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

Bilateral Control of Master-Slave Manipulators with Constant Time Delay

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Abstract— **This paper proposed a novel frame work for bilateral teleoperation systems with a multi-degree-of-freedom (DOF) nonlinear robotic system in master and slave side with constant time delay in communication channel. We actually extend the passivity based architecture upon the earlier work of [6] to improve position tracking and consequently transparency in the face of environmental contacts. The proposed controller employs a PID controller in each side to overcome some limitation of PD controller and guarantee good performance. Besides, we show that this new PID controller preserve the control passivity of the system. Simulation and experimental results show that PID controller tracking performance is better than PD controller tracking performance in slave/ environment contacts.**

I. INTRODUCTION

Over the past 3 decades, teleportation technologies have been gradually growing through the world. Teleportation is used in many applications such as space operation, handling of toxic and harmful materials, robotic surgery and underwater exploration. Teleoperation can be divided into the two main types, unilateral and bilateral. In unilateral teleportation, contact force feedback is not flow to the master. In bilateral teleoperation, the remote environment provides some necessary information by many different forms, including audio, visual displays, or tactile through the feedback loop to the master side. However, the contact force feedback (haptic feedback) can provides a better sense of teleprenses and as a consequences improve tasks performances.

In bilateral teleoperation, the master and the slave manipulators are connected via a communication channel and time delay is existed in transmission of information between the master and slave site. It is well known that the time delays in a closed loop system can destabilize a stable system [1].

This work was supported in part by the Department of Electrical Engineering, Science and Research Branch, Islamic Azad University.

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The first work solving time delay problem in teleoperation appeared in 1989. Anderson and Spong [2] proposed a new communication architecture based on the scattering theory to over come instability caused by time delay. They used a constant time delay through their communication block and design their system to be linear time invariant. Their control algorithm cannot deal with varying characteristics of the system. Neimeyer and Slotine [3] introduce the use of wave variables in teleoperation extended from scattering theory proposed by Anderson et al. [2]. Both of these approaches are based on passivity, which is a sufficient condition for stability. The key issue for these approaches is to make the non-passive communication medium with time delay passive

Although scattering approach or the equivalent wave variable formulations guarantee robust stability of the teleoperator, they deteriorate the tracking performance.

The ideal response (i.e. transparency) for the telerobotic system with time-varying delay in communication channel is definite as follows [4]:

1- The force that the human operator applies to the master robot is equal to the force reflected from the environment in the steady state. This can help operators to realize force sensation.

2- The master velocity/position is equal to the slave velocity/position in the steady state.

Chopra and Spong [5] proposed a new architecture which builds upon the scattering theory by using additional position control on both the master and slave sides. This new architecture has better position tracking and comparable force tracking abilities than the traditional teleoperator model of [2], [3]. In [6], [7] a new framework was introduced which utilize the PD controller over the delayed communication. Then using the controller passivity concept, the Lyapunov–Krasovskii technique, and Parseval's identity, passify the combination of the delayed communication and control blocks altogether robustly, as long as the delays are finite constants and an upper bound for the round-trip delay is known. Nuno *et al.* [8] shown that it is possible to control a bilateral teleoperation with simple PD-like controller and achieve stable behaviour under specific condition on control parameters. According to the complexity of the communication network, the backward and forward delays are not only time-varying but also asymmetric. In [9], [10] two different method based on PD controller have been presented to address these problems.

In this paper, the passivity based architecture of [6] is extended to improve position tracking and consequently transparency in the face of environmental contacts. In this regard, a PID controller is employed in each side to overcome some limitation of PD controllers such as disturbance rejection. The key feature of the proposed PID controller is that it preserves the control passivity of the system. For this purpose, we will use controller passivity, Parseval's identity, the Lyapunov–Krasovskii functional and Schur complement to show that the proposed PID controller with additional dissipation term will preserve the passivity of the system under some condition, as long as the time delays are constant.

The rest of this paper organized as follows. Section II describes passive bilateral teleoperation structure with constant time delay introduced by Lee *et al*. [6]. In Section III we describe the new control architecture based on PID controller and demonstrate its passivity. Furthermore, we used a Nicosia observer [12] to estimate the human hand forces when the master does not have force sensor. Section IV shows the simulation and experimental results. And finally Section V draws conclusions and gives some suggestion for future works.

II. Passive Bilateral Teleoperation Structure with Constant Time Delay

In [6] a novel control framework for bilateral teleoperation of a pair of multi-DOF nonlinear robotic systems with constant communication delays was proposed. The proposed bilateral teleoperation framework is shown in Figure1.

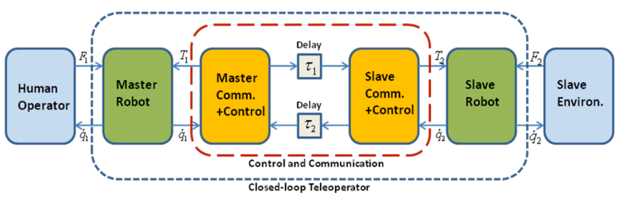

Fig. 1. The schematic of the closed-loop teleoperation system [6].

A bilateral teleoperation system which is shown in Fig.1 consists of five interacting subsystems: the human operator, the master manipulator, the control and communication block, the slave manipulator and the environment. The human operator commands via a master manipulator by exerting a force F_1 (F_h) to move it with velocity $\dot{q}_1$ which is sent to the slave manipulator through the communication block. A local control (T_2) on the slave side drives the slave velocity $\dot{q}_2$ towards the master velocity. If the slave contacts a remote environment and/or some external source, the remote force F_2 ($-F_e$) is transmitted back from the slave side and received at the master side as the force or control signal T_1 .

A. Modeling of Teleoperator with Constant Time Delay

Assuming absence of friction or other disturbances, the equation of motion for a pair of n-degree-of-freedom (DOF) nonlinear robotic systems is given as [6]

$$M_1(q_1)\ddot{q}_1 + C_1(q_1,\dot{q}_1)\dot{q}_1 = T_1(t)+F_1(t) \qquad (1)$$

$$M_2(q_2)\ddot{q}_2 + C_2(q_2,\dot{q}_2)\dot{q}_2 = T_2(t)+F_2(t) \qquad (2)$$

where $q_i(t),F_i(t),T_i(t)\in\Re^n$ are the configurations, human/environmental force, and controls, and $M_i(q_i),C_i(q_i,\dot{q}_i)\in\Re^{n\times n}$ are symmetric and positive-definite inertia matrices and Coriolis matrices, respectively, s.t. $\dot{M}_i(q_i)-C_i(q_i,\dot{q}_i)$ are skew-symmetric $(i=1,2)$. In [6] assumed that the gravity effects are either included in $F_1(t),F_2(t)$ or pre-compensated by the local controls

B. Control Objectives

The control objectives are designing the controllers $T_1(t),T_2(t)$ to achieve these two goals:

I. *master–slave position coordination*: if $(F_1(t),F_2(t))=0$,

$$q_E(t):=q_1(t)-q_2(t)\to 0, \quad t\to\infty \qquad (3)$$

II. *static force reflection*: with $(\ddot{q}_1(t),\ddot{q}_2(t),\dot{q}_1(t),\dot{q}_2(t))\to 0$

$$F_1(t)\to -F_2(t) \;\; or \;\; F_h(t)\to F_e(t) \qquad (4)$$

For safe interaction and coupled stability, the closed-loop teleoperator (1)-(2) should satisfy the following *energetic passivity*: there exists a finite constant $d\in\Re$ s.t.

$$\int_0^t [F_1^T(\theta)\dot{q}_1(\theta)+F_2^T(\theta)\dot{q}_2(\theta)]d\theta \ge -d^2 \quad \forall t\ge 0 \qquad (5)$$

i.e. maximum extractable energy from the two-port closed-loop teleoperator is bounded (see Fig. 1). Defining *controller passivity* [6],[7]: there exists a finite constant $c\in\Re$ s.t.

$$\int_0^t [T_1^T(\theta)\dot{q}_1(\theta)+T_2^T(\theta)\dot{q}_2(\theta)]d\theta \le c^2 \quad \forall t\ge 0 \qquad (6)$$

i.e., energy generated by the two-port controller (see Fig. 1) is always bounded.

Lemma 1 *For the mechanical teleoperator* (1)-(2), *controller passivity* (6) *implies energetic passivity* (5).

This lemma is proven in [6].

C. Control Design

It is shown in [6] that the master and slave controllers $T_1(t),T_2(t)$ in (7), (8) guarantee the master-slave coordination (3), bilateral force reflection (4), and energetic passivity (5).

$$T_1(t)=-K_v(\dot{q}_1(t)-\dot{q}_2(t-\tau_2))-(K_d+P_\varepsilon)\dot{q}_1(t)-K_p(q_1(t)-q_2(t-\tau_2)) \qquad (7)$$

$$T_2(t)=-K_v(\dot{q}_2(t)-\dot{q}_1(t-\tau_1))-(K_d+P_\varepsilon)\dot{q}_2(t)-K_p(q_2(t)-q_1(t-\tau_1)) \qquad (8)$$

where $\tau_1,\tau_2\ge 0$ are the forward and backward finite constant delays, $K_v,K_p\in\Re^{n\times n}$ are the symmetric and positive-definite proportional (P) and derivative (D) control gains, $P_\varepsilon\in\Re^{n\times n}$ is an additional damping ensuring master-slave coordination (3), and $K_d\in\Re^{n\times n}$ is the dissipation to passify the delayed P-action (i.e.with *Kp*) in (7)-(8). One possible selection for K_d is

$$K_d = \frac{\bar{\tau}_{rt}}{2} K_p \tag{9}$$

where $\bar{\tau}_{rt} \geq 0$ is an upper-bound of the round-trip delay $\tau_{rt} := \tau_1 + \tau_2$ s.t. $\bar{\tau}_{rt} \geq \tau_{rt}$.

III. The Proposed Control Scheme

In order to eliminate steady-state tracking error and improve the disturbance rejection when the slave contact to the environment, we extend PD to PID control. The integral term is added so that the system will have no steady-state error in the presence of constant disturbances. In sequel, the passivity of the presented control methodology is illustrated through rigorous mathematical analysis.

Adding an integral term and additional dissipation term K_{d2} to (7), (8) control low, the PID control low can be introduced as

$$T_1'(t) = -K_v(\dot{q}_1(t) - \dot{q}_2(t-\tau_2)) - K_p(q_1(t) - q_2(t-\tau_2)) - K_i\int_0^t (q_1(t) - q_2(t-\tau_2))dt - (K_d + K_{d2} + P_\varepsilon)\dot{q}_1(t) \tag{10}$$

$$T_2'(t) = -K_v(\dot{q}_2(t) - \dot{q}_1(t-\tau_1)) - K_p(q_2(t) - q_1(t-\tau_1)) - K_i\int_0^t (q_2(t) - q_1(t-\tau_1))dt - (K_d + K_{d2} + P_\varepsilon)\dot{q}_2(t) \tag{11}$$

The following theorem shows that the two local controllers $T_1'(t), T_2'(t)$ in (10), (11) guarantee energetic passivity (5) of the closed-loop teleoperator under the condition on K_{d2} which is given in (12).Note that K_p, K_v, K_i, K_d and K_{d2} are positive-definite diagonal matrixes.

Theorem 1:

Consider the nonlinear bilateral teleoperation system described by (1), (2) with the controllers (10), (11) under the condition (9). If the K_{d2} gain satisfying

$$(12)\ \forall\omega, \qquad K_{d2} \geq \frac{2\cos^2(\frac{\omega(\tau_1+\tau_2)}{4})}{\omega^2} K_i$$

Then the closed loop teleoperator is energetic passive.

Proof:

Following the same procedure in [6] to show energetic passivity of the close loop system, by substituting (10), (11) in the definition of controller passivity (6) we obtain

$$\int_0^t [T_1'^T(\theta)\dot{q}_1(\theta) + T_2'^T(\theta)\dot{q}_2(\theta)]d\theta \leq c^2 \quad \forall t \geq 0 \tag{13}$$

denoting the terms in integral (13) by $s_n(t)$ and substituting from (10), (11) yields

$$s_n(t) := s_d(t) + s_p(t) + s_i(t) + P(t) \tag{14}$$

where $s_d(t)$, $s_p(t)$ and $s_i(t)$ are the supply rates associated to the delayed D-action, delayed P-action (+dissipation K_d) and delayed I-action (+dissipation K_{d2}) and defined by

$$(15)\ s_d(t) := -\dot{q}_1^T(t)K_v\dot{q}_1(t) + \dot{q}_1^T(t)K_v\dot{q}_2(t-\tau_2) - \dot{q}_2^T(t)K_v\dot{q}_2(t) + \dot{q}_2^T(t)K_v\dot{q}_1(t-\tau_1)$$

$$(16)\ s_P(t) := -\dot{q}_1^T(t)K_d\dot{q}_1(t) - \dot{q}_1^T(t)K_p(q_1(t) - q_2(t-\tau_2)) - \dot{q}_2^T(t)K_d\dot{q}_2(t) - \dot{q}_2^T(t)K_p(q_2(t) - q_1(t-\tau_1))$$

$$(17)\ s_i(t) := -\dot{q}_1^T(t)K_{d2}\dot{q}_1(t) - \dot{q}_1^T(t)K_i\int_0^t(q_1(t) - q_2(t-\tau_2))dt - \dot{q}_2^T(t)K_{d2}\dot{q}_2(t) - \dot{q}_2^T(t)K_i\int_0^t(q_2(t) - q_1(t-\tau_1))dt$$

and $P(t)$ is the following positive-definite quadratic form:

$$P(t) := \begin{pmatrix}\dot{q}_1(t)\\ \dot{q}_2(t)\end{pmatrix}^T \begin{bmatrix}P_\varepsilon & 0\\ 0 & P_\varepsilon\end{bmatrix}\begin{pmatrix}\dot{q}_1 t)\\ \dot{q}_2(t)\end{pmatrix} \tag{18}$$

It is shown in [6] that

$$\int_0^t s_d(\theta)d\theta \leq -V_v(t) + V_v(0) \tag{19}$$

where $V_v(t) \geq 0\ \forall t \geq 0$ is a Lyapunov-Krasovskii functional for delayed systems defined by

$$V_v(t) := \sum_{i=1}^{2}\frac{1}{2}\int_{-\tau_i}^{0}\dot{q}_i^T(t+\theta)K_v\dot{q}_i(t+\theta)d\theta \geq 0 \tag{20}$$

Besides, if the condition (9) is satisfied, it is shown in [6] that

$$\int_0^t s_p(\theta)d\theta \leq -V_p(t) + V_p(0) \tag{21}$$

where $V_P(t) \geq 0\ \ \forall t \geq 0$ defined as

$$V_p(t) := \frac{1}{2}q_E^T(t)K_p q_E(t) \tag{22}$$

with $q_E(t) = q_1(t) - q_2(t)$.

Considering the fact that $q_i(t), \dot{q}_i(t) = 0\ \ \forall t \in (-\infty, 0]$ then, the energy generation by s_i the supply rate in (17) can be written as

$$\begin{aligned}\int_0^t s_i(\lambda)d\lambda = &-\int_{-\infty}^{\infty}\dot{q}_1^T(\lambda)K_{d2}\dot{q}_1(\lambda)d\lambda - \int_{-\infty}^{\infty}\dot{q}_2^T(\lambda)K_{d2}\dot{q}_2(\lambda)d\lambda\\ &-\int_{-\infty}^{\infty}\dot{q}_1^T(\lambda)[K_i\int_{-\infty}^{t}(q_1(\xi) - q_2(\xi-\tau_2))d\xi\ ]d\lambda\\ &-\int_{-\infty}^{\infty}\dot{q}_2^T(\lambda)[K_i\int_{-\infty}^{t}(q_2(\xi) - q_1(\xi-\tau_1))d\xi\ ]d\lambda\end{aligned} \tag{23}$$

Now, denoting the Fourier transform of $q_i(t), (i=1,2)$ by $V_i(j\omega) = \int_{-\infty}^{\infty}q_i(t)e^{-j\omega t}dt = \int_0^t q_i(t)e^{-j\omega t}dt$, and using Parseval's identity, we have

$$\begin{aligned}\int_{-\infty}^{\infty}\dot{q}_1^T(\lambda)K_{d2}\dot{q}_1(\lambda)d\lambda &= \frac{1}{2\pi}\int_{-\infty}^{\infty}(-j\omega)V_1^*(j\omega)K_{d2}(j\omega)V_1(j\omega)d\omega\\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty}(\omega^2)V_1^*(j\omega)K_{d2}V_1(j\omega)d\omega\end{aligned} \tag{24}$$

$$\begin{aligned}&\int_{-\infty}^{\infty}\dot{q}_l^T(\lambda)[K_i\int_{-\infty}^{t}(q_l(\xi) - q_k(\xi-\tau_k))d\xi\ ]d\lambda\\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty}(-j\omega)V_l^*(j\omega)K_i[\frac{1}{j\omega}V_l(j\omega) + \pi V_l(0)\delta(\omega) - \frac{e^{-j\omega\tau_k}}{j\omega}V_k(j\omega) + \pi V_k(0)\delta(\omega)]d\omega\\ &= -\frac{1}{2\pi}\int_{-\infty}^{\infty}V_l^*(j\omega)K_i[V_l(j\omega) - e^{-j\omega\tau_k}V_k(j\omega)]d\omega, \quad (l,k) = \{(1,2),(2,1)\}\end{aligned} \tag{25}$$

Where V_i^* is complex conjugate transpose of a complex vector V_i and using the fact that $\omega\delta(\omega) = 0$. Then, substituting (24), (25) in (23) we have

$$\int_0^t s_i(\lambda)d\lambda = -\frac{1}{2\pi}\int_{-\infty}^{\infty}\omega^2 V_1^*(j\omega)K_{d2}V_1(j\omega)d\lambda$$
$$-\frac{1}{2\pi}\int_{-\infty}^{\infty}\omega^2 V_2^*(j\omega)K_{d2}V_2(j\omega)d\lambda \quad (26)$$
$$-\frac{1}{2\pi}\int_{-\infty}^{\infty}V_1^*(j\omega)K_i[e^{-j\omega\tau_2}V_2(j\omega)-V_1(j\omega)]d\omega$$
$$-\frac{1}{2\pi}\int_{-\infty}^{\infty}V_2^*(j\omega)K_i[e^{-j\omega\tau_1}V_1(j\omega)-V_2(j\omega)]d\omega$$
$$= -\frac{1}{2\pi}\int_{-\infty}^{\infty}\begin{bmatrix}\overline{V}_1(j\omega)\\ \overline{V}_2(j\omega)\end{bmatrix}^T H(j\omega)\begin{bmatrix}\overline{V}_1(j\omega)\\ \overline{V}_2(j\omega)\end{bmatrix}d\omega$$

where, $H(j\omega)\in C^{2n\times 2n}$ is given by

$$H(jw) = \begin{bmatrix}\omega^2 K_{d2} - K_i & \frac{K_i}{2}(e^{j\omega\tau_1}+e^{-j\omega\tau_2})\\ \frac{K_i}{2}(e^{-j\omega\tau_1}+e^{j\omega\tau_2}) & \omega^2 K_{d2}-K_i\end{bmatrix} \quad (27)$$

for more detail see [6]. Since $H(j\omega)$ is Hermitian, then using Schur complement, $H(j\omega)$ is positive-semidefinite if and only if

$$\omega^2 K_{d2} - K_i \geq 0 \rightarrow \omega^2 K_{d2} \geq K_i \quad (28)$$

and

$$(\omega^2 K_{d2} - K_i) \geq \frac{(e^{-j\omega\tau_1}+e^{j\omega\tau_2})}{2}\frac{(e^{j\omega\tau_1}+e^{-j\omega\tau_2})}{2}K_i(\omega^2 K_{d2}-K_i)^{-1}K_i \quad (29)$$
$$= \frac{1+\cos\omega(\tau_1+\tau_2)}{2}K_i(\omega^2 K_{d2}-K_i)^{-1}K_i$$

which is always true if

$$(30)\quad K_{d2} \geq \frac{2\cos^2(\frac{\omega(\tau_1+\tau_2)}{4})}{\omega^2}K_i$$

Selecting the gain according to (30) ensures that $\int_0^t s_i(\lambda)d\lambda$ is semi-negative. Therefore, by summing up (18) and (19) with (21) and the fact that $V_v(t)\geq 0$, $V_p(t)\geq 0$ and $P(t)\geq 0$ $\forall t \geq 0$ we have

$$\int_0^t [(T_1'^T(\theta)\dot{q}_1(\theta) + T_2'^T(\theta)\dot{q}_2(\theta)$$
$$\leq -V_v(t)+V_v(0)-V_p(t)+V_p(0)-\int_0^t P(\theta)\,d\theta \quad (31)$$
$$\leq V_v(0)+V_p(0) =: c^2$$

with c a finite constant. Thus the controller passivity is proved. Finally, from lemma 1, energetic passivity (5) of the closed loop teleoperator follows.

It is also conclude that, if $(\ddot{q}_1(t),\ddot{q}_2(t),\dot{q}_1(t),\dot{q}_2(t))\rightarrow 0$, then from the master-slave robot dynamics (1),(2) and their controls (10),(11), we get $F_1(t)\rightarrow -F_2(t)\rightarrow -K_p(q_1(t)-q_2(t))-K_i\int_0^t(q_1(t)-q_2(t))dt$ where $\dot{q}_i(t-\tau_i)\rightarrow 0$ and $q_i(t-\tau_i)\rightarrow q_i(t)$.

A. Hand Force Observer

In our master-slave system, master is a two-DOF joystick and has uncoupled motions about the two axes due to its gimbal-based design. In the experiment, the measurements of hand/master forces $F_1(F_h)$ are required. Because our master do not have force sensor, we use a nonlinear state observer to estimate $F_1(F_h)$. Now, choosing $x_1 = q_1$ and $x_2 = \dot{q}_1$, we write the master dynamic in state-space as

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = M_1^{-1}(q_1)(-C_1(x_1,x_2)x_2 + T_1(t) + F_1(t)) \quad (32)$$

The Nicosia observer, which is used to estimate the hand forces F_1 or joint velocity $\dot{q}_1$, described by [12], [13]:

$$\dot{\hat{x}}_1 = \hat{x}_2 + k_2 e$$
$$\dot{\hat{x}}_2 = M_1^{-1}(x_1)(-C_1(x_1,\dot{\hat{x}}_1)\dot{\hat{x}}_1 + T_1(t) + K_1 e) \quad (33)$$
$$e = x_1 - \hat{x}_1$$

where e is the output observation error, k_2 is a positive scalar constant and K_1 is a symmetric positive-definite matrix. This nonlinear observer uses joint position and the portion of the joint torque which comes from the controller to estimate the external applied joint force. It is shown in [12] that the observer is asymptotically stable and the error dynamic is:

$$(34)\quad M_1\ddot{e} + k_2 M_1\dot{e} + K_1 e = F_1$$

in steady state, $\ddot{e} = \dot{e} = 0$. In this result, at low frequency the hand force is estimated as $\overline{F}_1 = K_1 e$.

IV. SIMULATIONS AND EXPRIMENTS

A. Simulation

In order to evaluate the effectiveness of the proposed control scheme in this paper, the controller has been applied to a pair of 2-link planar RR robot arm. The robot dynamic was given in [14]. The lengths of serial links for both master and slave robots are considered as $a_1 = a_2 = 1.3m$, and the links inertia were taken as $m_1 = 0.8, m_2 = 2.3\ kg$. To evaluate the system's contact behavior, a virtual soft ball is installed in the slave environment at $x = 0.5$. The ball is modeled like a spring-damper system with the spring and damping gains as 100N/m and 0.2 Ns/m. The controller gains are chosen such that the close loop system behaves as a critical damping system. In this regard, the gains K_p, K_v and K_i are selected $K_v = 40I_{2\times2}$, $K_p = (\frac{K_v}{2})^2 = 400I_{2\times2}$, $K_i = I_{2\times2}$ and the P_ε is also set to zero. Note that, K_i has been chosen small so that the third-order error dynamic is close to the second-order error dynamic without this term (i.e., a dominant pole analysis can be performed). The delays were selected as $\tau_1 = \tau_2 = 1$ sec. Then, according to the condition (9), (12): $(K_d, K_{d2}) = (400I_{2\times2}, 5I_{2\times2})$. Because the observer should have fast response, the observer gains are taken as $(K_1,k_2) = (450I_{2\times2}, 45)$. The scenario is set up such that the operator moves the master robot from the home position in x-direction to $(x,y) = (1,0)$ in Cartesian space and returns it to imitate a sinusoidal input. The slave trying to follow these commands is steered towards an obstacle. As a result, force information is generated and sent back to the master.

The simulation result for the two joint positions and force tracking are shown in Fig. 2 and 3. The force and position tracking and consequently transparency are satisfactory. The master position in Cartesian space and the slave contact force is also shown in Fig. 4. As shown in Figs.3 and 4, when the slave robot contact with the ball at $x = 0.5$, the contact force is reflected to the master. Moreover, when the slave robot move in free motion the interaction force is zero.

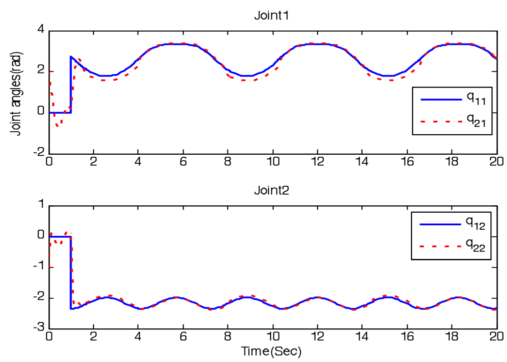

Fig. 2. The master and the slave joint positions with PID controller for 2-DOF robots

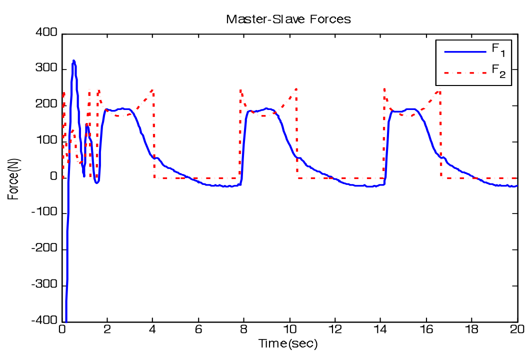

Fig. 3. The estimation of human force F_1 and the environmental force F_2 with PID controller for 2-DOF robots

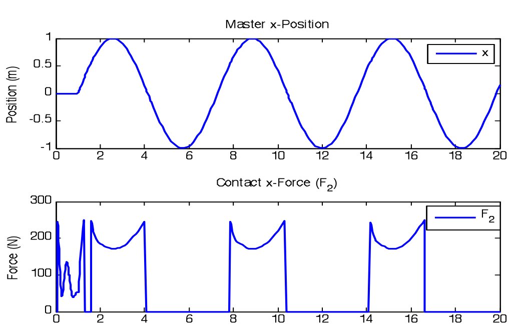

Fig. 4.The master position in Cartesian space and the slave contact force

B. Expriment

In the experiment, a two-DOF Logitech joystick with forcefeedback is used as the master. The joystick has uncoupled motions about the two axes due to its gimbal-based design. We use joystick only in x-direction. The slave, which is constructed as a virtual robot, is a 1_DOF robot with prismatic joint. The slave dynamic is assumed to be $M_2 = 0.7\,kg, C_2 = 2\,Ns/m$. The communication delays and the environment model are the same as before. The virtual slave robot and a ball as environment placed in front of it, is shown in Figure 5. The integration of the master-slave teleoperation is accomplished through the MATLAB Simulink environment.

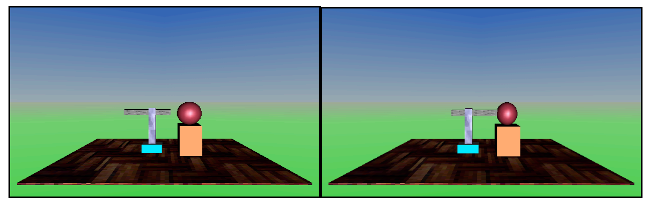

Fig. 5. Virtual slave robot with a ball as environment in free motion and contact situation

The scenario is set up such that the operator moves the joystick away from the home position at $x = 0$ to the position $x = 0.8$ and returns it to imitate a step input. The slave trying to follow these commands is steered towards an obstacle. As a result, force information is generated and sent back to the master. The control parameters are chosen as $(K_p, K_v, K_i) = (25,10,1)$ and the P_ε is also set to zero. Then, According to (9), (12), $(K_d, K_{d2}) = (25,5)$ are chosen. The observer gains are taken as $(K_1, k_2) = (250,100)$. The experimental results for position and force tracking are shown in Figs. 6 and 7.

To study the contribution of the proposed controller we implement the conventional controller (PD) (7), (8) with the same control parameters. Fig.8 and Fig.9 show the results. The position tracking performance is not good however the force tracking is a bit better the PID controller.

To sum up, it is clear that the proposed PID controller makes a significant improvement in the position tracking and rejects the constant disturbance (environmental contact) as a result, transparency is improved.

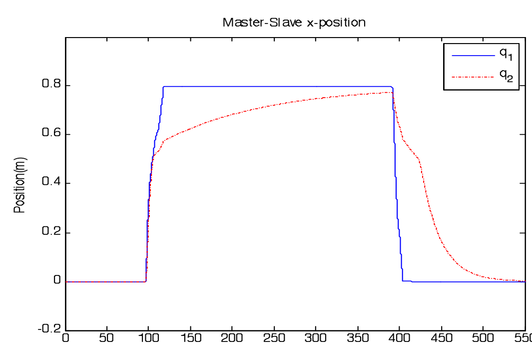

Fig. 6. The master and the slave positions with PID controller for 1-DOF robots

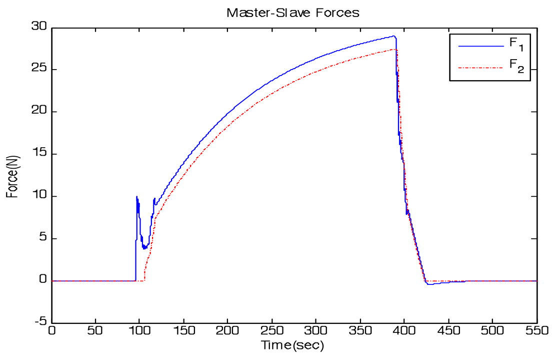

Fig. 7. The estimated human force F_1 and the environmental force F_2 with PID controller for 1-DOF robots

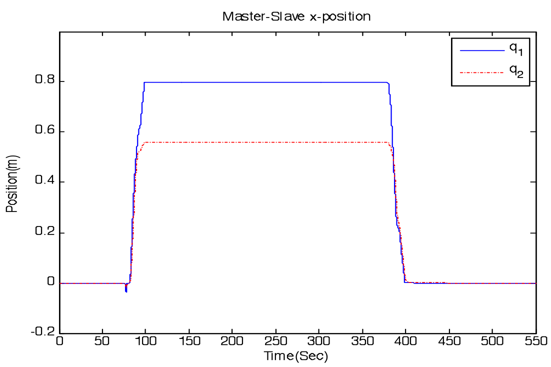

Fig. 8. The master and the slave positions with PD controller for 1-DOF robots

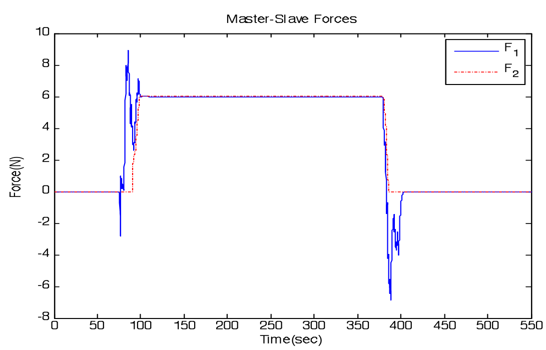

Fig. 9. The estimated human force F_1 and the environmental force F_2 with PD controller for 1-DOF robots

V. Conclusion

To achieve transparency and stability for a teleoperation system with time delay in communication channel, a new PID control architecture was proposed in this paper. The new architecture extends PD to PID architecture that allows the controller to reject the constant disturbance. We showed that the new PID architecture preserve the energetic passivity under the condition on additional dissipation term. Since the master does not have force sensor, a state observer is used to estimate the human force. The new controller provides better transparency which is measured in terms of position and force tracking ability of bilateral system. Evaluating the performance of this controller architecture with real slave robot remains for future work.

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