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Performance Improvement of Force Feedback in Bilateral Teleoperation with PD controller

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***Abstract*— This paper deals with the performance improvement of force feedback in bilateral teleoperation with PD controller. In traditional PD structures, the force feedback is simply determined by the position and velocity of the master and the slave manipulators, which may induce large resistance forces to the operator even in free motion. In this paper, a novel PD bilateral controller is proposed to tackle this problem. By incorporating a distance variable in the controller, we show that the appropriate force feedback can be obtained which still guarantees the system stability. To validate the proposed algorithm, an experiment is also carried out on our single degree of freedom teleoperation system. The results indicate that this strategy is effective for safe teleoperation missions.**

I. INTRODUCTION

TEleoperation has widespread applications in many areas such as space mission, undersea exploration, hazardous environment, telesurgery, etc [1-6]. The teleoperation system is commonly composed of the operator, master manipulator, communication channel, slave manipulator and task environment. In bilateral teleoperation, the master controls the slave to move, and the slave feed back the contact force to the master at the same time. The bilateral control strategy offers the operator a good tactile interface, by which the operator can feel the slave operation status, just like he stays in the real task environment.

Stability plays an important role in a bilateral teleoperation with time delay, and this problem has been studied by many researchers. For example, Anderson and Spong [7] presented a control law by using passivity and scattering theory, which overcame the instability caused by time delay. These results were then extended by Niemeyer and Slotine in [8], where the notion of wave variables was introduced to get a new configuration for bilateral teleoperation. The scattering-wave variable method can guarantee the stability of the bilateral teleoperation, but its tracking performance was not satisfactory as introduced in [9]. Recently in [9-15], various of PD controllers were presented to solve the tracking problem.

In 2004, Imaida et al. [10] carried out a bilateral teleoperation experiment successfully in Engineering Test Satellite 7(ETS-VII), in which the following PD controller is used;

$$\begin{aligned}\tau_m &= K_m\left(x_m - x_s\left(t-T_2\right)\right) + P_m\dot{x}_m \\ \tau_s &= K_s\left(x_s - x_m\left(t-T_1\right)\right) + P_s\dot{x}_s\end{aligned} \tag{1}$$

where K_m and K_s are proportional gains, and P_m and P_s are damping gains. T_1 and T_2 are the time delays from the master to the slave, and the slave to the master, respectively.

Lee et al. [11] then proposed another PD control framework and proved the passivity of the system. Their controller is

$$\begin{aligned}\tau_m &= K_m\left(x_m - x_s\left(t-T_2\right)\right) + P_m\dot{x}_m \\ &\quad + D_m\left(\dot{x}_m - \dot{x}_s\left(t-T_2\right)\right) \\ \tau_s &= K_s\left(x_s - x_m\left(t-T_1\right)\right) + P_s\dot{x}_s \\ &\quad + D_s\left(\dot{x}_s - \dot{x}_m\left(t-T_1\right)\right)\end{aligned} \tag{2}$$

where D_m and D_s are the differential gains, and other parameters have the same meaning with (1).

In addition, Nuño et al. [12-13] proved that the master and slave velocities asymptotically converged to zero in free motion for several different PD controllers including (1) and (2).

However, there exists an inherent problem in the systems with the PD controller (1) and (2). Note that the master control force τ_m is determined by the position and velocity differences of the master and slave manipulators, which are commonly not zero in the process of the operation. So τ_m exists not only in contact motion, but also in free motion. In particular, if the operator moves the master manipulator rapidly in free motion, τ_m will become very large. This will affect the judgement of the operator since the force he feels may be generated either by the collision with the object or simply in free motion.

In order to have appropriate force feedback for the operator in the bilateral teleoperation, we make the proposition as folllows:

Proposition 1: The control force τ_m should:

1) be as small as possible in free motion when the slave manipulator is far away from the object, such that the operate can hardly feel it.

2) become large gradually when the slave manipulator moves close to the object, so as to let the operator operate carefully.

3) be as large as possible when hard contact occurs.

To satisfy Proposition 1, we propose a new controller by incorporating a distance variable into the master controller. The main idea can be summarized as follows: by installing a range sensor on the slave manipulator [16], the distance

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between the slave manipulator and the object can be attained. Then by setting the proportional and differential gains small enough, we make the distance terms as the primary factor in τ_m. As such, the appropriate force feedback can be achieved, and the operator can make proper decision in the operation based on the force feedback. In our previous work[17], we studied the force feedback when the slave manipulator approached the object, to reduce the influence of the large time delay for nonlinear systems, while in this paper we focus on linear time-invariant(LTI) systems with different distance function and slave control force, and study the improvement of the force feedback in all operation stages.

This paper is organized as follows: the preliminaries including bilateral dynamics, presumption conditions and basis lemmas are given in Section II. The bilateral PD controller with the slave distance is described in Section III. The stability is analyzed in Section IV. The experiments are shown in Section V, and a discussion is followed in Section VI. Finally, conclusions are drawn in Section VII.

II. PROBLEM FORMULATION

A. Dynamics in bilateral teleoperation

The linear dynamics of the master and slave manipulators are given by

$$\begin{aligned} M_m\ddot{x}_m + B_m\dot{x}_m = F_h - \tau_m \\ M_s\ddot{x}_s + B_s\dot{x}_s = \tau_s - F_e \end{aligned} \tag{3}$$

where M_m, B_m are the master inertia and damping, and M_s, B_s are the slave inertia and damping. F_h is the operator force and F_e is the environment force. τ_m and τ_s are the master and slave control force. x_i, $\dot{x}_i$, $\ddot{x}_i$ are the position, velocity, acceleration, respectively. Where $i = m$ for the master and $i = s$ for the slave.

Note that the position, velocity and acceleration of the manipulators, and the distance signal measured by the sensor are time dependent in this paper, and we omit the variable t in the equations for simplicity, and only express it in the delay case.

B. Assumptions

For a teleoperator system, we make the following assumptions.

Assumption 1: The position of the master and slave manipulators can be measured by the sensors.

Assumption 2: The distance between the slave manipulator and the object is bounded, i.e.

$$d \in [0, \infty) \tag{4}$$

where d stands for the distance.

Assumption 3: The energy applied by the human operator on the master manipulator, and exerted by the slave manipulator on the environment is passive, i.e. $\exists\ U_h,\ U_e \in \mathbb{R}_+$, $\forall\ t \geq 0$

$$\int_0^t \dot{x}_m F_h d\theta \leq U_h \qquad -\int_0^t \dot{x}_s F_e d\theta \leq U_e \tag{5}$$

Assumption 4: If the variable P is bounded, The energy applied by P on the master manipulator is passive, i.e. $\exists$ $U_d \in \mathbb{R}_+$, $\forall\ t \geq 0$

$$-\int_0^t \dot{x}_m P d\theta \leq U_d \tag{6}$$

C. Lemmas

The following lemmas will be used in this paper.

Lemma 1 [12]: For any signals x, y and any T, $\alpha > 0$, the following inequality holds.

$$\int_0^t x^t(s)\left[\int_0^T y(s-\sigma)\,d\sigma\right] ds \leq \frac{\alpha}{2}\|x\|_2^2 + \frac{T^2}{2\alpha}\|y\|_2^2 \tag{7}$$

where $\|\cdot\|_2$ is the L_2-norm of the signal.

Lemma 2 [11]: For any two positive numbers c, d and any $\alpha > 0$, the following inequality holds.

$$2cd \leq \alpha c^2 + \frac{d^2}{\alpha} \tag{8}$$

III. CONTROLLER DESIGN

According to Assumption 1, the position of the master and slave manipulator can be measured. We assume that there exists time delay T in a bilateral teleoperation, then the position signal arriving at the slave site is

$$x_{sd} = x_m(t-T) \tag{9}$$

and the position signal arriving at the master site is

$$x_{md} = x_s(t-T) \tag{10}$$

We design the master control force based on PD controller as

$$\tau_m = K_m(x_m - x_{md}) + D_m(\dot{x}_m - \dot{x}_{md}) + K_d Q \tag{11}$$

where $K_m \in \mathbb{R}_+$ is the master proportional gain, $D_m \in \mathbb{R}_+$ is the master differential gain, $K_d \in \mathbb{R}_+$ is the distance signal gain, and Q is a nonnegative number which is defined as

$$Q = \begin{cases} 0 & \phi < d \\ \phi - d & 0 < d < \phi \\ \varepsilon & d = 0 \end{cases} \tag{12}$$

where $\phi\ \in [0, \infty)$ is a threshold value, $d\ \in [0, \infty)$ is the distance between the slave manipulator and the object, and $\varepsilon\ \in [0, \infty)$ is a large number, so as to get a large force feedback in contact motion.

The PD mode in [12] is adopted for the slave control force as

$$\tau_s = K_s(x_{sd} - x_s) + D_s(\dot{x}_{sd} - \dot{x}_s) \tag{13}$$

where $K_s \in \mathbb{R}_+$ is the slave proportional gain, and $D_s \in \mathbb{R}_+$ is the slave differential gain.

The control block diagram is shown in Fig. 1. where $f_{d\to Q}$ is denoted by(12).

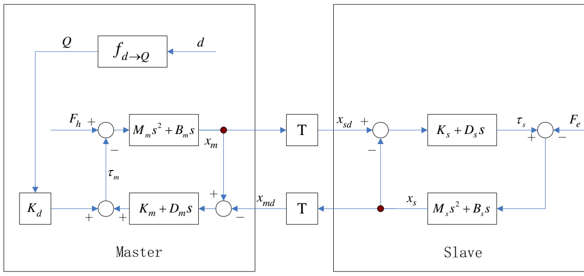

Fig. 1. Control block diagram.

IV. STABILITY ANALYSIS

Theorem 1: Consider the bilateral teleoperation system (3), and the control force (11) and (13), when Assumptions 1-4 are satisfied, the system is stable provided that the following condition holds.

$$\left(B_m + \frac{D_m}{2}\right)\left(B_s + \frac{D_s}{2}\right) > K_m K_s T^2 \tag{14}$$

Proof: From Assumption 2 and the definition of Q, it is clear that Q is bounded. The following inequality holds according to assumption 4:

$$-\int_0^t \dot{x}_m Q d\theta \le U_d \tag{15}$$

Define the following storage function for the system as

$$\begin{aligned} V =& \frac{1}{2}M_m\dot{x}_m^2 + \frac{K_m}{2K_s}M_s\dot{x}_s^2 + \frac{K_m}{2}\left(x_m - x_s\right)^2 \\ &+ \left(U_h - \int_0^t \dot{x}_m F_h d\theta\right) \\ &+ \frac{K_m}{K_s}\left(U_e + \int_0^t \dot{x}_s F_e d\theta\right) \\ &+ \frac{K_m D_s}{2K_s}\int_{t-T}^t \dot{x}_m^2 d\theta + \frac{D_m}{2}\int_{t-T}^t \dot{x}_s^2 d\theta \\ &+ K_d\left(U_d + \int_0^t \dot{x}_m Q d\theta\right) \end{aligned} \tag{16}$$

From Assumption 3 and (15) , it is easy to show that V is nonnegative. The derivative of V is given by

$$\begin{aligned} \dot{V} =& M_m\dot{x}_m\ddot{x}_m - \dot{x}_m F_h + \frac{K_m}{K_s}M_s\dot{x}_s\ddot{x}_s \\ &+ \frac{K_m}{K_s}\dot{x}_s F_e + K_m\left(x_m - x_s\right)\left(\dot{x}_m - \dot{x}_s\right) \\ &+ \frac{K_m D_s}{2K_s}\left(\dot{x}_m^2 - \dot{x}_m^2\left(t-T\right)\right) \\ &+ \frac{D_m}{2}\left(\dot{x}_s^2 - \dot{x}_s^2\left(t-T\right)\right) + K_d Q\dot{x}_m \end{aligned} \tag{17}$$

Substituting the manipulator dynamics (3) into (17), we get

$$\begin{aligned} \dot{V} =& \dot{x}_m\left(-B_m\dot{x}_m - \tau_m\right) + \frac{K_m}{K_s}\dot{x}_s\left(-B_s\dot{x}_s + \tau_s\right) \\ &+ K_m\left(x_m - x_s\right)\left(\dot{x}_m - \dot{x}_s\right) \\ &+ \frac{K_m D_s}{2K_s}\left(\dot{x}_m^2 - \dot{x}_m^2\left(t-T\right)\right) \\ &+ \frac{D_m}{2}\left(\dot{x}_s^2 - \dot{x}_s^2\left(t-T\right)\right) + K_d Q\dot{x}_m \end{aligned} \tag{18}$$

Substituting (11), (13) into (18), the derivative reduces to

$$\begin{aligned} \dot{V} =& -\left(B_m + D_m\right)\dot{x}_m^2 - \frac{K_m}{K_s}\left(B_s + D_s\right)\dot{x}_s^2 \\ &+ K_m\left(x_{md} - x_s\right)\dot{x}_m + K_m\left(x_{sd} - x_m\right)\dot{x}_s \\ &+ D_m\dot{x}_{md}\dot{x}_m + \frac{K_m D_s}{K_s}\dot{x}_{sd}\dot{x}_s \\ &+ \frac{K_m D_s}{2K_s}\left(\dot{x}_m^2 - \dot{x}_m^2\left(t-T\right)\right) \\ &+ \frac{D_m}{2}\left(\dot{x}_s^2 - \dot{x}_s^2\left(t-T\right)\right) \end{aligned} \tag{19}$$

Using the transformation

$$\int_0^T \dot{x}_i\left(t-\theta\right)d\theta = x_i\left(t-T\right) - x_i \qquad i = m, s \tag{20}$$

Together with (21) and (22)

$$\dot{x}_s\left(t-T\right)\dot{x}_m \le \frac{1}{2}\left(\dot{x}_s^2\left(t-T\right) + \dot{x}_m^2\right) \tag{21}$$

$$\dot{x}_m\left(t-T\right)\dot{x}_s \le \frac{1}{2}\left(\dot{x}_m^2\left(t-T\right) + \dot{x}_s^2\right) \tag{22}$$

We get

$$\begin{aligned} \dot{V} \le& -\left(B_m + \frac{D_m}{2}\right)\dot{x}_m^2 - \frac{K_m}{K_s}\left(B_s + \frac{D_s}{2}\right)\dot{x}_s^2 \\ &+ K_m\dot{x}_m\int_0^T \dot{x}_s\left(t-\sigma\right)d\sigma \\ &+ K_m\dot{x}_s\int_0^T \dot{x}_m\left(t-\sigma\right)d\sigma \end{aligned} \tag{23}$$

Integrating (23) from 0 to t, and letting $t \to \infty$, we get

$$\begin{aligned} \int_0^t \dot{V}ds \le& -\left[\left(B_m + \frac{D_m}{2}\right) - K_m\left(\frac{\alpha_m}{2} + \frac{T^2}{2\alpha_s}\right)\right]\|\dot{x}_m\|_2^2 \\ &-\left[\frac{K_m}{K_s}\left(B_s + \frac{D_s}{2}\right) - K_m\left(\frac{\alpha_s}{2} + \frac{T^2}{2\alpha_m}\right)\right]\|\dot{x}_s\|_2^2 \end{aligned}$$

where Lemma 1 is used in the above derivation. In addition, from the above inequation, we can see that if

$$B_m + \frac{D_m}{2} > K_m\left(\frac{\alpha_m}{2} + \frac{T^2}{2\alpha_s}\right) \tag{24}$$

$$\frac{K_m}{K_s}\left(B_s + \frac{D_s}{2}\right) > K_m\left(\frac{\alpha_s}{2} + \frac{T^2}{2\alpha_m}\right) \tag{25}$$

the semi-definite function V is bounded, and the system is stable. Using lemma 2, we get (14) from (24) and (25), which have a positive solution α_m, α_s.

This completes the proof. ■

Next, we turn to the case where the communication delays forward and backward are different. In this case, (9) and (10) become

$$x_{sd} = x_m (t - T_1) \tag{26}$$

$$x_{md} = x_s (t - T_2) \tag{27}$$

where T_1 and T_2 denote the communication delay forward and backward, respectively. The following theorem summarizes the main result.

Theorem 2: Consider the bilateral teleoperation system with time delay T_1 and T_2 described by (3), and the control force (11) and (13), when Assumptions 1-4 are satisfied, the system is stable provided that the following condition holds.

$$\left(B_m + \frac{D_m}{2}\right)\left(B_s + \frac{D_s}{2}\right) > \frac{1}{4} K_m K_s (T_1 + T_2)^2 \tag{28}$$

Proof: Define the following storage function for the system

$$\begin{aligned} V = &\frac{1}{2} M_m \dot{x}_m^2 + \frac{K_m}{2K_s} M_s \dot{x}_s^2 + \frac{K_m}{2}(x_m - x_s)^2 \\ &+ \left(U_h - \int_0^t \dot{x}_m F_h d\theta\right) \\ &+ \frac{K_m}{K_s}\left(U_e + \int_0^t \dot{x}_s F_e d\theta\right) \\ &+ \frac{K_m D_s}{2K_s}\int_{t-T_1}^t \dot{x}_m^2 d\theta + \frac{D_m}{2}\int_{t-T_2}^t \dot{x}_s^2 d\theta \\ &+ K_d\left(U_d + \int_0^t \dot{x}_m Q d\theta\right) \end{aligned} \tag{29}$$

Following the same line with proof of theorem 1, we have

$$\begin{aligned} \dot{V} \le &-\left(B_m + \frac{D_m}{2}\right)\dot{x}_m^2 - \frac{K_m}{K_s}\left(B_s + \frac{D_s}{2}\right)\dot{x}_s^2 \\ &+ K_m \dot{x}_m \int_0^{T_2} \dot{x}_s (t - \sigma) d\sigma \\ &+ K_m \dot{x}_s \int_0^{T_1} \dot{x}_m (t - \sigma) d\sigma \end{aligned} \tag{30}$$

Integrating (30) from 0 to t, and letting $t \to \infty$, we can see that the semi-definite function V is bounded if

$$B_m + \frac{D_m}{2} > K_m\left(\frac{\alpha_m}{2} + \frac{T_1^2}{2\alpha_s}\right) \tag{31}$$

$$\frac{K_m}{K_s}\left(B_s + \frac{D_s}{2}\right) > K_m\left(\frac{\alpha_s}{2} + \frac{T_2^2}{2\alpha_m}\right) \tag{32}$$

From (31) and (32), we can get (28).

This completes the proof. ■

Next, we consider the delay-free case. In this case, (11) and (13) become

$$\tau_m = K_m (x_m - x_s) + D_m (\dot{x}_m - \dot{x}_s) + K_d Q \tag{33}$$

$$\tau_s = K_s (x_m - x_s) + D_s (\dot{x}_m - \dot{x}_s) \tag{34}$$

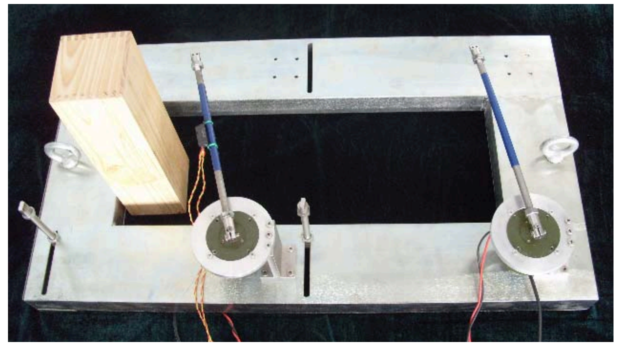

Fig. 2. Experiment system.

then the following corollary can be easily achieved and the proof follows verbatim the steps of the proof of Theorem 1 with the same nonnegative function (16).

Corollary 1: Consider the bilateral teleoperation system (3), and the control force (33) and (34), when Assumptions 1-4 are satisfied, the system is stable provided that the following condition holds.

$$\left(B_m + \frac{D_m}{2}\right)\left(B_s + \frac{D_s}{2}\right) > 0 \tag{35}$$

We can get easily from the theorem 1, 2 and Corollary 1 that the parameters of the controllers can be adjusted optionally under the condition that (14), (28) and (35) are satisfied. Thus, the K_m and D_m can be set as small as possible, and τ_m is mainly determined by Q so as to satisfy Proposition 1.

V. EXPERIMENTS

In this section, we apply our proposed algorithms on an experiment system. The experiment was carried out on a single degree of freedom bilateral teleoperation platform, which is shown in Fig. 2. Its main components are USB2812 control board, 70LY53 torque motor, and ADS-50/5 actuator produced by Maxon Co.; A 2D120X range sensor produced by Sharp Co. is installed on the slave manipulator to measure the distance between the slave manipulator and an object (a wooden box is used in the experiment system), whose detection range is from 0 to 30 centimeters. In Fig. 2, the right motor and its link are taken as the master manipulator, and the left motor and its link are taken as the slave manipulator.

In the experiment, we set two cases to compare the performance of the traditional PD controller and our proposed algorithm. The traditional controller (2) is used in case one, and the proposed control method in this paper is verified in case two. We perform two tests in case two: test A and test B; test A uses the same K_m, D_m as case one, and test B uses smaller K_m, D_m than case one. The experiment parameters in case 1 and case 2 are shown in Tab. I and Tab. II, respectively. For simplicity, the forward and backward time delays are set to be identical ($T = 0.5s$). Note that all these parameters satisfy (14).

TABLE I

EXPERIMENT PARAMETERS (CASE ONE)

B_m	K_m	D_m	P_m	B_s	K_s	D_s	P_s
0.1	2.2	4.4	5.5	0.1	2.2	4.4	5.5

TABLE II

EXPERIMENT PARAMETERS (CASE TWO)

test	B_m	K_m	D_m	K_d	B_s	K_s	D_s	ϕ	ε
A	0.1	2.2	4.4	10	0.1	2.2	4.4	10	50
B	0.1	0.22	0.88	10	0.1	2.2	4.4	10	50

At the beginning of the experiments, the slave manipulator is far away from the wooden box, and both manipulators have the same starting points. As the operator moves the master manipulator, the slave manipulator is controlled to move toward the wooden box. In this stage, the manipulators run in free motion. As the time goes by, the slave manipulator gradually approaches the wooden box, and eventually come into contact with it. After approximately 2s, the manipulators are dragged to the origin. Then, the tracking performance and the force feedback are analyzed.

The tracking curves in case one and case two are shown in Fig. 3, Fig. 5 and Fig. 7, respectively, where the solid line denotes the position of the master manipulator, and the dotted line denotes the position of the slave. We can see that the systems are stable in two cases, and the slave can track the master basically. Since the parameters of the controllers are not optimal, the tracking performance is not good enough. However, the focus here is in the improvement of the force feedback, and the parameter optimization is not within the sphere of this paper.

Fig. 4 shows both changes of the distance in the slave site and the corresponding driving voltage in the master motor in case one, and the same variables in case two are shown in Fig. 6 and Fig. 8. Note that the driving voltage reflects the master control force τ_m since the motor is controlled by torque mode; the higher the drive voltage is, the larger the output force is. Here, the resolution of ADS-50/5 actuator is 12 bits, and its voltage range is $-10V$ to $10V$, it means that the input value changes from 0 to 4096 and output voltage changes from $-10V$ to $10V$, and we obtain the control parameters according to the input value of the actuator in the experiment. In addition, the scale of the voltage in Fig. 4 is bigger than ones in Fig. 6 and Fig. 8, so that it is more clear to see the voltage changes.

In Fig. 4, the traditional PD controller (2) is used. Thus, τ_m has nothing to do with the distance between the slave manipulator and the wooden box, but is only determined by the position and velocity differences of the master and slave manipulators. When the slave manipulator goes forward, the force feedback is positive, and vice versa, thus two peeks in different directions appear in a round trip.

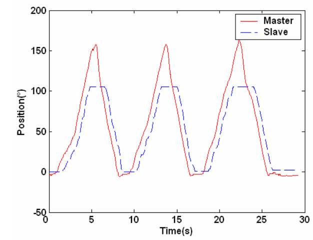

Fig. 3. Tracking curves (case one).

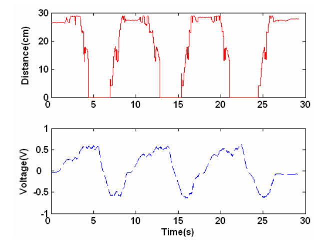

Fig. 4. The object distance and master motor voltage(case one).

Moreover, the feedback voltage is rather low even in contact motion. Therefore, the operator does not know when the slave manipulator encounters the wooden box. This situation changes in Fig. 6 and Fig. 8, in which the proposed controller (11) and (13) are used.Comparing Fig.6 with Fig. 8, we can see that big K_m and D_m affect the feedback voltage, it is obvious in Fig. 6 that when the slave manipulator is far away from the object during 6.5-8s, 14-17s and 22-24s, the feedback voltage will ripple around 0V, just like the changes in Fig. 4. However, this is improved with small K_m and D_m, and appropriate voltages feedback is obtained. In Fig. 8, when the slave manipulator runs in free motion during 0-3s, 9-13s, 18-20s and 24.5-27.5s, τ_m is approximately zero; when approaching the wooden box during 3-5.5s, 13-14s and 20-21s, τ_m becomes larger and larger; then in the contact stage at 5.5-9s, 14-16s, 21.5-24.5s, τ_m arrives its peek force. It can be concluded that τ_m satisfies Proposition 1 and the operator can obtain the appropriate resistance force in different operation stages. Note that the range of the sensor is 0 to 30 centimeters, thus the value is still 30 if the distance exceeds 30 centimeters, and the jumps in the curves are caused by the sensor error.

VI. DISCUSSION

The distance between the slave manipulator and the object is measured by the range sensor, and is passed through the communication channel, therefore the signal arriving at the master site is actually a delayed one. However, the transmission process of the distance signal is not considered here and we only focus on the feasibility and the effect of this new scheme. Therefore, we assume that the distance can be well estimated provided that the communication time delay, the master command series, the position and velocity of the master and slave manipulators are known. This assumption will not destroy the system stability, since the distance information is independent of the bilateral exchange

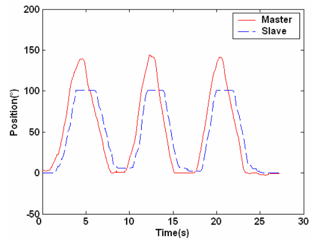

Fig. 5. Tracking curves (test A in case two).

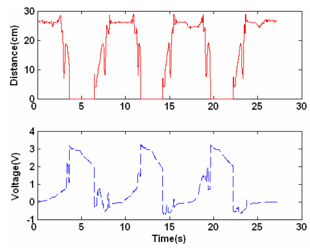

Fig. 6. The object distance and master motor voltage(test A in case two).

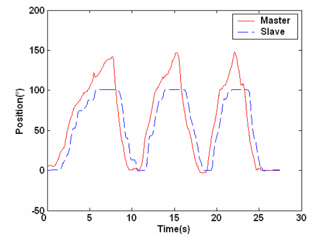

Fig. 7. Tracking curves (test B in case two).

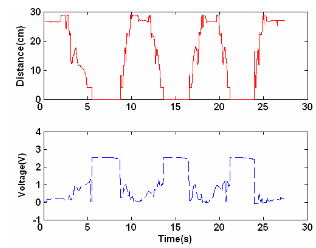

Fig. 8. The object distance and master motor voltage(test B in case two).

information, namely, the force and the position. However, the consideration of the communication delay for the slave distance will be more precise, and this will be our future work.

It is also worthwhile to mention that in this paper, we convert the slave distance information to force feedback, and the aim is to improve the force feedback in bilateral teleoperation with PD controller. Therefore, transparency of the bilateral control scheme is not discussed here, and more emphasis is placed on the tracking performance. Moreover, the optimal controller parameters, the motion in soft environment and the stability analysis with a variable time delay are not considered in this study. These issues will also be studied in our future research.

VII. CONCLUSION

The operator feels the operation status in the remote site via the force feedback in bilateral teleoperation. But the appropriate force feedback cannot be obtained via traditional PD methods since the force feedback is simply determined by the position and velocity of the master and the slave manipulators. In this paper, we use the basic frame of the PD controller, and incorporate a distance variable in the controller to improve the force feedback. By using this method, the appropriate force feedback can be obtained. Thus, it is an effective approach for the operator to make proper decision in teleoperation. The proposed control method is validated on a single degree of freedom experiment system, and the results show that this method is feasible and effective.

REFERENCES

[1] P. F. Hokayem, M. W. Spong, “Bilateral teleoperation: an historical survey,” *Automatica*, vol. 42 pp. 2035-2057, Sep. 2006.

[2] M. Nohmi, “Space teleoperation using force reflection of communication time delay,” in *Proc. IEEE Int. Conf. Intelligent Robots and Systems*, Las Vega, 2003, pp. 2809-2814.

[3] M. A. Jord and J. L. Bustamante, “On the presence of nonlinear oscillations in the teleoperation of underwater vehicles under the influence of sea wave and current,” in *Proc. American Control Conference*, New York, 2007, pp. 894-899.

[4] K. A. Manocha, N. Pernalete and R. V. Dubey, “Variable position mapping based assistance in teleoperation for nuclear cleanup,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Seoul, 2001, pp. 374 - 379.

[5] K. Kawashima, K. Tadano, G. Sankaranarayanan and B. Hannaford, “Model-based passivity control for bilateral teleoperation of a surgical robot with time delay,” in *Proc. IEEE Int. Conf. Intelligent Robots and Systems*, Nice, 2008, pp. 1427 - 1432.

[6] O. M. Palafox and M. W. Spong, “Bilateral teleoperation of a formation of nonholonomic mobile robots under constant time delay,” in *Proc. IEEE Int. Conf. Intelligent Robots and Systems*, St. Louis, 2009, pp. 2821 - 2826.

[7] Robert J. Anderson and Mark W. Spong, “Bilateral control of teleoperators with time delay,” *IEEE Trans. Automatic Control*, vol. 34, pp. 494-501, May. 1989.

[8] G. Niemeyer and J. E. Slotine, “Stable adaptive teleoperation,” *IEEE J. Oceanic Engineering*, vol. 16, pp. 152-162, Jan. 1991.

[9] N. Chopra, M. W. Spong, R. Ortega and N. E. Barabanov, “On tracking performance in bilateral teleoperation,” *IEEE Trans. Robotics*, vol. 22, pp. 861-866, Aug. 2006.

[10] T. Imaida, Y. Yokokohji, T. Doi and T. Yoshikawa, “Ground-Space bilateral teleoperation of ETS-VII robot arm by direct bilateral coupling under 7-s time delay condition,” *IEEE Trans. Robotics and Automation*, vol. 20, pp. 499-511, Jun. 2004.

[11] D. Lee and M. W. Spong, “Passive bilateral teleoperation with constant time delay,” *IEEE Trans. Robotics*, vol. 22, pp. 269-281, Apr. 2006.

[12] E. Nuño, R. Ortega, N. Barabanov and L. Basañez, “A globally stable PD controller for bilateral teleoperators,” *IEEE Trans. Robotics*, vol. 24, pp. 753-758, Aug. 2008.

[13] E. Nuño and L. Basañez, “Nonlinear bilateral teleoperation: stability analysis,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Kobe, 2009, pp. 3718-3723.

[14] N. Chopra, M. W. Spong and R. Lozano, “Synchronization of bilateral teleoperators with time delay,” *Automatica*, vol. 44, pp. 2142-2148, Mar. 2008.

[15] E. Nuño, R. Ortega and L. Basañez, “An adaptive controller for nonlinear teleoperators,” *Automatica*, vol. 46, pp. 155-159, Jan. 2010.

[16] K. Kim, W. K. Chung and M. C. Cavusoglu, “Description of instantaneous restriction space for multi-DOFs bilateral teleoperation system using position sensors in unstructured environments,” *IEEE Trans. Robotics*, vol. 25, pp. 1150-1158, Oct. 2009

[17] Y. Wang, F. Sun, H. Liu, Y. Li and H. Min, ”Bilateral teleoperation based on range sensor,” *Robot* (in Chinese), to be published.