Position and Force Control of Teleoperation System Based on PHANTOM Omni Robots

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Abstract—**Good position and force tracking are two important performance requirements on teleoperation system. However the external disturbances significantly reduce the position and force tracking accuracy of teleoperation system. To solve this problem, this paper proposes a control method which combines backstepping control and PID control to control the teleoperation system based on PHANTOM Omni robots. PID controller is designed for the master robot to achieve force tracking, while backstepping controller is designed for the slave robot to achieve position tracking. Furthermore, simulations are conducted using MATLAB to verify the proposed method for the teleoperation system, composed of two PHANTOM Omni robots. Simulation results show that when the system is subjected to external disturbances, the proposed method which combines backstepping control and PID control can ensure system stability and keep good position and force tracking performance.**

Index Terms—**PHANTOM Omni robots, teleoperation system, backstepping controller, PID controller, position tracking, force tracking**

I. Introduction

In the human-computer interaction process, the computer responses to the behaviors of the operator (including the operator's position, action and speed). Meanwhile, through this process reacts to the operator through haptic devices. This is called force feedback. As the interaction interface of the operator and the environment, haptic devices allow the operator to get force feedback of touching real object. PHANTOM Omni Robot is such a force feedback device, which has been widely applied in education, health care, gaming, engineering and many other fields [1]. Alejandro Jarillo-Silva [2] analyzed the mechanical structure of a single PHANTOM Omni device as well as its hardware and software environment. Haptically enabled surgical simulation can allow users to be trained with realistic haptic feedback in the medical field [3]. Lan Wang *et al.* [4] explored an upper limb rehabilitaion training method based on virtual reality interaction.

In robot teleoperation field, force feedback device is a key equipment, The operator can achieve precise control of slave robot through the master robot. Then the master feeds certain force information to the operator, so that the operator can always change the control strategy. Even without visual feedback, the operator can perform tasks in distant places by via force feedback, which increases the reliability of robot operation. Liu *et al*. [5] get a nonlinear adaptive bilateral control method to solve the robot system with uncertain dynamics and Kinematics problems.

In this paper, the teleoperation system that composed of two PHANTOM Omni robots is taken as control object. The force and position control are achieved by a method which combines backstepping control and PID control. PID controller is designed for the master robot to achieve the force tracking of the slave robot, while backstepping controller is designed for the slave robot to track the position of the master robot. It should be pointed out that CCD camera feedback and real-time haptic feedback control method was employed in [6], and the inverse dynamics control of teleoperation was considered [7]. In this paper we will investigate the position and force control at the same time for the teleoperation system which is composed of two PHANTOM Omni robots.

The rest of this paper is organized as follows. We first introduce the model of teleoperation based on PHANTOM Omni. Next, PID and backstepping controllers are designed for the master and slave robots to study the stability and motion tracking convergence of the teleoperation system. Simulation results in Section III show that the slave can follow the position of the master. Besides, the force tracking performance is good. The paper is concluded in Section IV.

II. Model of Teleoperation Based on PHANTOM Omni

In this section, firstly the dynamic model of one robot is given, then the model is extended to the dynamic and model of teleoperation system based on two Phantom Omni robots.

When interacting with a human and an environment, the joint-space nonlinear dynamic models for an n-DOF robot can be described as:

$$\mathrm{M}(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+d=\tau \qquad (1)$$

where $q\in R^{n\times 1}$ is the joint angle position, $M(q)\in R^{n\times n}$ is the symmetric positive definite inertia matrix,

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$C(q,\dot{q}) \in R^{n\times n}$ is the matrix representing Corioli and centrifugal term, $G(q) \in R^{n\times 1}$ represents gravity term, $\tau \in R^{n\times 1}$ is control inputs torques.

For brevity, let's define:

$$V(q,\dot{q}) = C(q,\dot{q})\dot{q} + G(q) \tag{2}$$

Substituting (2) into (1), we have:

$$M(q)\ddot{q} + V + d = \tau \tag{3}$$

Based on the dynamic model of one robot, the force exerted on the master robot f_m, and the force exerted on the slave robot f_s are introduced. Then the joint-space nonlinear dynamic models for teleoperation system with an *n*-DOF master robot and an n-DOF slave robot can be described as:

$$\begin{aligned} M_m(q_m)\ddot{q}_m + V_m(q_m,\dot{q}_m) &= \tau_m + f_m + d_m \\ M_s(q_s)\ddot{q}_s + V_s(q_s,\dot{q}_s) &= \tau_s - f_s + d_s \end{aligned} \tag{4}$$

where "m" and "s" representing the master and slave robot, V_m and V_s are matrices representing Coriolis and centrifugal and gravity terms, f_m denotes the force that the operator applies to the master robot, f_s is the force the environment applies to the slave robot, τ_m and $\tau_s \in R^{n\times 1}$ are control inputs (torques), d_m and d_s are disturbances.

In this paper we will investigate the teleoperation system which is composed of two PHANTOM Omni robots (Sensable, USA). PHANTOM Omni robot is appropriate haptic device to realize the teleoperation system. IEEE 1394 Firewire port is used for communication interface [8]. For single PHANTOM Omni robot, its structure is given in Fig. 1.

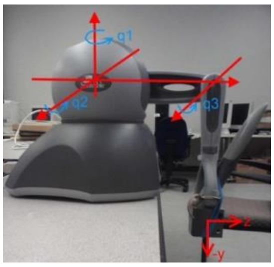

Figure 1. Phantom Omni robot

According to the structure of the PHANTOM Omni robot, Coriolis and centrifugal and gravity terms are given as [9]:

$$V(q,\dot{q}) = [V_1, V_2]^T = C(q,\dot{q})\dot{q} + G(q) \tag{5}$$

To simplify the simulation process, joint 2 of the master and the slave robot is locked, substituting Joint q_1, q_3 angle into (5), we can get:

$$V_1 = -2a_1\dot{q}_1\dot{q}_3\sin(2q3) + 2a_3\dot{q}_1\dot{q}_3\cos(2q3) + a_4\dot{q}_1\dot{q}_3\cos(q3) - a_5\dot{q}_1\dot{q}_3\sin(q3)$$

$$V_2 = 2a_2\dot{q}_1^2\cos(q3)\sin(q3) - a_3\dot{q}_1^2\cos(2q3) - \frac{1}{2}a_4\dot{q}_1^2\cos(q3) + \frac{1}{2}a_5\dot{q}_1^2\sin(q3) + a_7\sin(q3) + a_8\cos(q3)$$

The symmetric positive definite inertia matrix is as follows:

$$M(q) = \begin{bmatrix} a_1 + a_2c_{23} + a_3s_{23} + a_4c_3 + a_5s_3 & 0 \\ 0 & a_6 \end{bmatrix} \tag{6}$$

$$\begin{aligned} &c_i = \cos(q_i), s_i = \sin(q_i), \\ &c_{2,i} = \cos(2q_i), s_{2,i} = \sin(2q_i), \quad i = 1,2,3\ldots \end{aligned} \tag{7}$$

III. Design of Controllers

The control problem in teleoperation system is that the slave can exactly reproduce the master's position trajectory for the environment and the master can accurately display the slave-environment contact force to the human. Block diagram of teleoperation control system is shown in Fig. 2.

Figure 2. Block diagram of teleoperation control system

Specially, in this paper, our proposed control scheme is that the master robot transmits f_m (the force that the operator applies to the master) and q_m (position command variable) to slave robot by the traditional PID controller. At the same time, the slave robot tracks the position information and transmits the reaction force back to the master robot through the communication channel by backstepping controller.

A. *Design of PID Controller for the Master Robot*

The principle of the traditional PID control is simple and it is widely used to achieve complex force tracking. Thus, PID control is chosen to achieve force tracking for the master robot.

Define the tracking error of force as e_f:

$$e_f = f_m - f_s \tag{8}$$

Take PID control law as:

$$\tau_m = k_p e_f + k_i \int e_f dt + k_d \dot{e}_f \tag{9}$$

where k_p, k_i and k_d are constants greater than zero. Once e_f occurs, the controller will reduce it immediately.

B. *Design of Backstepping Controller for the Slave Robot*

The basic idea of backstepping control is decomposing complex nonlinear system into subsystems, whose number does not exceed the order of the system. Then design Lyapunov functions for each subsystem and virtual control inputs, then go back to the entire system until the entire control law is designed. Using backstapping control, the closed-loop system can meet the expectations of dynamic and static performance indicators.

Backstepping control method allows the system to meet the conditions of Lyapunov stability theory. The error is asymptotically stable, thus ensuring the stability of the global system. That's why we chose backstepping controller to achieve the tracking position for the slave robot.

$$M_s(q_s)\ddot{q}_s + V_s(q_s,\dot{q}_s) = \tau_s - f_s + d_s \tag{10}$$

$$\mathrm{M}_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + G(q_s) + d_s = \tau_s \tag{11}$$

Define:

$$x_1 = q_s = \begin{bmatrix} q_{s1} \\ q_{s3} \end{bmatrix} \; x_2 = \dot{q}_s = \begin{bmatrix} \dot{q}_{s1} \\ \dot{q}_{s3} \end{bmatrix} \tag{12}$$

where q is joint angle variable vector, $\dot{q}$ is joint angular velocity vector. $\ddot{q}$ is angular acceleration vector.

The force that the environment applies to the slave f_s is shown as:

$$f_s = b_w \frac{dx_s}{dt} + c_w x_s$$

where, b_w is equivalent damping, c_w is equivalent elasticity.

Substituting (12) into (10), we can obtain:

$$\begin{aligned} &\dot{x}_2 = \ddot{q}_s = -M_s^{-1}V_s + M_s^{-1}d_s - M_s^{-1}f_s + M_s^{-1}\tau_s \\ &\dot{x}_1 = x_2 \end{aligned} \tag{13}$$

By transformation, we have:

$$\begin{aligned} &\dot{x}_1 = x_2 \\ &\dot{x}_2 = f(x,t) + b(x,t)u \\ &b(x,t) = M_s^{-1}(x_1) \\ &f(x,t) = -M_s^{-1}(x_1)V_s - M_s^{-1}(x_1)f_s + M_s^{-1}d_s \end{aligned}$$

Define:

$$\begin{aligned} &z_1 = x_1 - z_d \\ &z_2 = x_2 + \lambda_1 z_1 - \dot{z}_d \\ &\dot{z}_1 = \dot{x}_1 - \dot{z}_d \end{aligned} \tag{14}$$

where, Z_d is the command variable to track. There we have:

$$\begin{aligned} \tau_s &= \frac{1}{b(x,t)}[-f(x,t) - \lambda_2 z_2 - z_1 - \lambda_1 \dot{z}_1 + \ddot{z}_d] \\ &= M_s(M_s^{-1}V_s - M_s^{-1}d_s + M_s^{-1}f_s - \lambda_2 z_2 - z_1 - \lambda_1 \dot{z}_1 + \ddot{z}_d) \\ &= V_s - d_s + f_s + M_s(\ddot{z}_d - z_1 - \lambda_2 z_2 - \lambda_1 \dot{z}_1) \end{aligned} \tag{15}$$

Define a Lyapunov function as:

$$V_1 = \frac{1}{2}z_1^2 \tag{16}$$

Substituting (14) into (16), we can get:

$$\dot{V}_1 = -\lambda_1 z_1^2 + z_1 z_2 \tag{17}$$

Define a Lyapunov function again:

$$V_2 = V_1 + \frac{1}{2}z_2^2 \tag{18}$$

Because:

$$\dot{z}_2 = f(x,t) + b(x,t)u + \lambda_1 \dot{z}_1 - \ddot{z}_d$$

Substitute (14) into (18) and define the equation

$$\dot{V}_2 = -\lambda_1 z_1^2 - \lambda_2 z_2^2 \le 0$$

to make the system meet the Lyapunov stability theory conditions. Finally, the following equation can be obtained:

$$\tau_s = M_s(q_s)\ddot{q}_s + V_s(q_s,\dot{q}_s) + f_s - d_s$$

IV. Simulation Study

Two PHANTOM Omni robots are used in simulations of the teleoperation system. To simplify the simulation process, joint 2 of the master and the slave robot is locked, where l_1=l_2=135mm are the first and second arm length. a_1 to a_8 are constants, whose specific values are listed in Table I.

TABLE I. PHANTOM Omni Parameters

parameters	value	parameters	value
a_1	$6.11\times10^{-3}\pm0.9\times10^{-3}$	a_2	$-2.89\times10^{-3}\pm0.43\times10^{-3}$
a_3	$-4.24\times10^{-3}\pm1.01\times10^{-3}$	a_4	$3.01\times10^{-3}\pm0.52\times10^{-3}$
a_5	$2.05\times10^{-3}\pm0.15\times10^{-3}$	a_6	$1.92\times10^{-3}\pm0.23\times10^{-3}$
a_7	$1.60\times10^{-3}\pm0.05\times10^{-3}$	a_8	$-8.32\times10^{-3}\pm2.78\times10^{-3}$

In the simulation, the initial positions of master and slave robot are set as:

$$q_m = \begin{bmatrix} q_{m1} \\ q_{m3} \end{bmatrix} = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}, q_s = \begin{bmatrix} q_{s1} \\ q_{s3} \end{bmatrix} = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$$

The initial force that operator applies to the master is set as:

$$f_m = \begin{bmatrix} 40sin\left(\frac{\pi}{40}\right) \\ 20sin\left(\frac{\pi}{20}\right) \end{bmatrix}$$

The force that environment applies to the slave is

$$f_s = b_w \frac{dx_s}{dt} + c_w x_s$$

where $b_w = 30$ and $c_w = 1500$.

The disturbance for the master robot is set as:

$$d_m = [0.025sint, 0.025sint]^T$$

The disturbance for the slave robot is set as:

$$d_s = [0.025sint, 0.025sint]^T$$

Repeatedly adjust the controller parameters by experience, the dynamic performance and accuracy are the best when controller parameters have the values shown in Table II.

TABLE II. Controller Parameters

k_p	k_i	k_d	λ_1	λ_2	b_w	c_w
300	30	0.5	150	150	30	1500

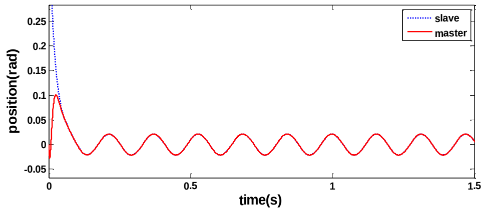

Figure 3. Position tracking of joint 1.

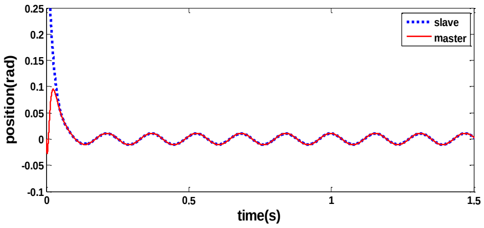

Figure 4. Position tracking of joint 3.

The simulation results are shown in Fig. 3, Fig. 4. The joint 1 and 3 keep good position tracking performance immediately until simulation ends.

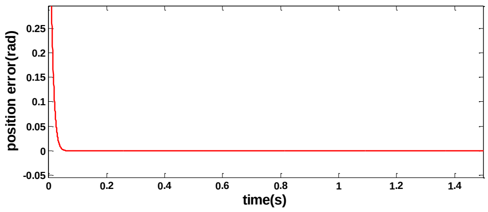

Figure 5. Position error of joint 1.

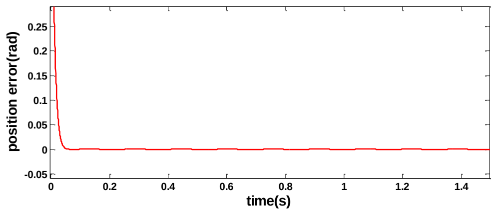

Figure 6. Position error of joint 3.

The simulation results about position tracking are shown in Fig. 5, Fig. 6. The position error converges to zero at about 0.03s, and keeps zero until simulation ends, which demonstrates that the tracking performance is good.

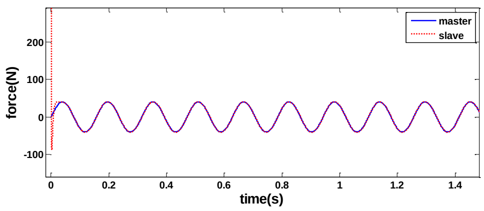

Figure 7. Force tracking of joint 1.

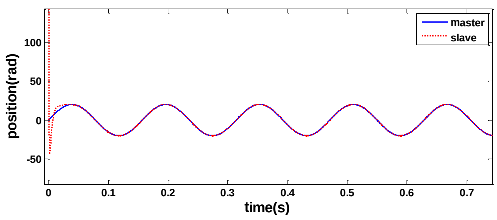

Figure 8. Force tracking of joint 3.

The simulation results about force tracking are shown in Fig. 7- Fig. 8. The force tracking synchronized at about 0.05s, and keeps good force tracking performance until simulation ends.

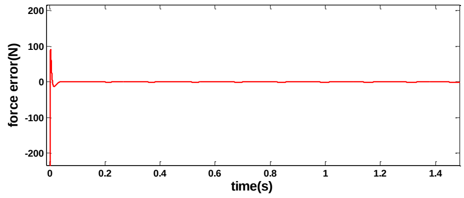

Figure 9. Force error of joint 1.

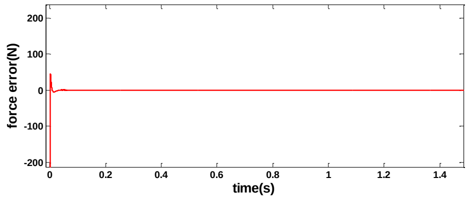

Figure 10. Force error of joint 3.

The simulation results about force error are shown in Fig. 9, Fig. 10. The force error converges to zero at about 0.03s, and keeps zero until simulation ends, which shows that the force tracking performance is good.

All of the above results show that when using the backstepping combining PID control method, the teleoperation system based on PHANTOM Omni robot is stable and can achieve good position and force tracking performance.

V. CONCLUSION

In order to achieve good position and force tracking performance in teleoperation system, this paper proposes a control method which combines backsteppingcontrol and PID control. Simulation results show that when the system is subject to external disturbances, the proposed method can ensure system stability, and get a good position and force tracking performance. In the actual teleoperation system, time delay is another important factor affecting the accuracy of the position and force tracking, how to come up with an effective control method, to overcome time delay remains as our future work.

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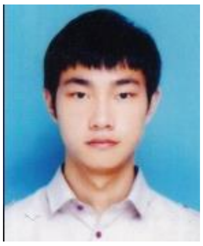

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