BILATERAL CONTROL OF MASTER-SLAVE MANIPULATOR SYSTEM USING TIME DELAY CONTROL

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Abstract: A prototype of dual arm master-slave manipulator system has been developed for use in a hot-cell at Korea Atomic Energy Research Institute. The slave manipulator can handle a 25 kgf payload in any posture, where the gravity force of remote tools or handling equipment has a great impact on the position error which produces the unnecessary force that operator does not have to feel. In this work, we applied a time delay controller for bilateral teleoperaiton of the manipulator system. Experimental results show that the time delay controller has good performance of the position tracking as well as force reflection.

1 INTRODUCTION

The use of remotely operated manipulators and other mechanical devices as replacements for human workers in hazardous environment is a growing field of research. In particular, master-slave manipulators have been extensively used in the nuclear industries governed by the ALARA principle for more than five decades. The master manipulator is an input device which interfaces with a human operator on one side and with a slave manipulator on the other. Bilateral force-reflecting control plays a key support role in a successful dexterous manipulator for master-slave manipulators. Great increases in the performance of master-slave manipulator systems can be achieved through a good design of the mechanical hardware and a proper implementation of the embedded control strategies.

Recently, we developed a prototype master-slave manipulator system for integrated demonstration of Pyroprocess which is a technology for refining nuclear materials from spent nuclear fuels using an electrochemical method in a molten salt bath at high temperature (Lee, Park, Lee, Kim & Kim, 2010). The Pyroprocess demonstration facility has a completely sealed argon gas-filled cell, with dimensions 40.3 × 4.8 × 6.4 m (L × W × H), where direct access by human operators is not possible during operation due to the high toxicity of argon gas. Therefore, all the operation and maintenance of process equipment must be performed remotely through master-slave manipulation.

Position-based bilateral control of master-slave manipulator system using PD controller has been mainly applied in the real field teleoperation system for practical reasons. However, the control performance will be degraded in case of existence of disturbances. In the controller, the position error occurs significantly due to the change of the gravity force of handling equipments. Therefore, it produces unnecessary force reflected to an operator owing to the nature of position error based force reflection.

To achieve a good tracking performance as well as highly transparent control, we applied Time Delay Control (TDC) for master-slave teleoperation. TDC has been proposed as an effective control method for nonlinear time-varying systems with unknown dynamics and/or unpredictable disturbances (Youcef-Toumi and Ito, 1990) and its stability was proven by Youcef-Toumi (1992) and Jung, Chang and Kang (2007). Hasia and Gao (1990) applied TDC to robot position control. Chang, Kim and Park (2004) used TDC to force/position control for robot manipulator. Song and Byun (2000) suggested a time delay controller with a variable reference model to improve the transient response characteristics and verified its performance on the BLDC motor position control. Recently, to overcome the performance degradation of the TDC in presence of nonlinear friction, Han and Chang (2010) proposed TDC with gradient estimator.

In this paper, we applied TDC to bilateral control of master-slave teleoperation system and verified its performance through experimental studies. This

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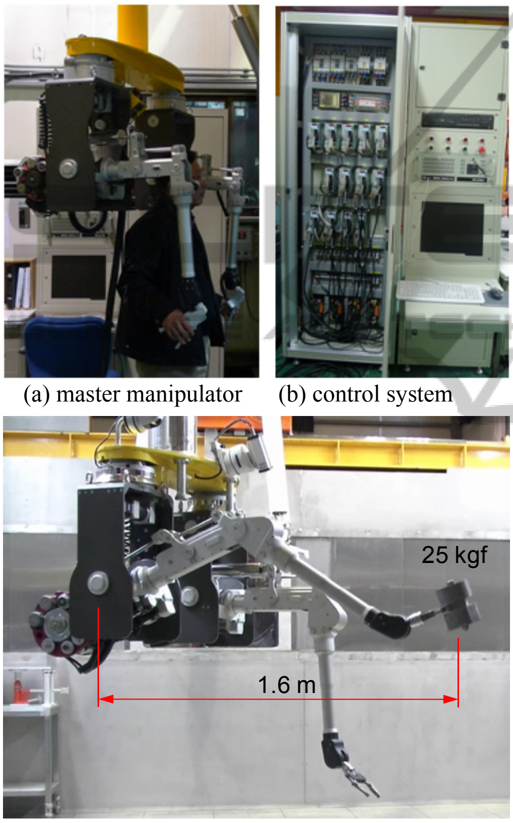
paper is organized as follows. Section 2 describes a prototype master-slave manipulator system and it control system. TDC is introduced in section 3. Section 4 illustrates experimental results of the TDC. The conclusion is described in the final section.

2 TELEOPERATION SYSTEM

2.1 Master-slave Manipulator System



(a) master manipulator (b) control system

(c) slave manipulator

Figure 1: Master-slave teleoperation system.

Figure 1 shows a master-slave servo-manipulator system, which have identical kinematic structures, except for link lengths, drive system, and end-effector type. Each arm of the master and the slave manipulators was designed with a 6-DOF serial link mechanism with all revolute joints, and power to each joint is transmitted through a cable from a corresponding motor mounted to a base frame. The slave manipulator can hold a 25 kg object in any pose, whereas the master manipulator reflects forces of up to 5 kgf to the operator. To use the teleoperation system, an operator manipulates the master arm while viewing the equipment or objects through an operating window or camera system.

2.2 Control System Hardware

Figure 2 shows configuration of the main control system. It consists of a control PC, four 8-axes motion control boards, motor drivers, a manual console, a pendant, etc. Servo motors adopted in the master-slave servo-manipulator are controlled by using a torque control mode for realizing a bilateral force reflection control.

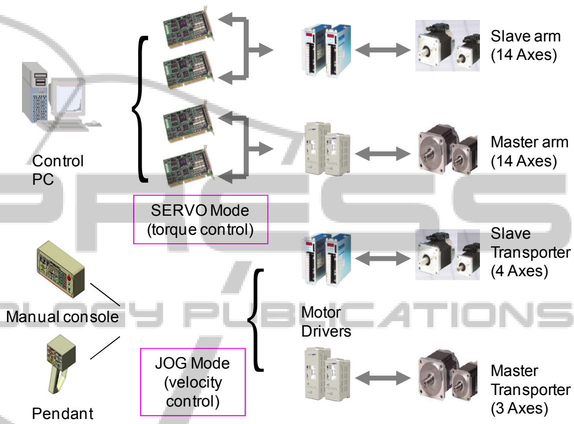


Figure 2: Configuration of the motion control system.

A GUI operation program was written in Visual C++ 6.0 and runs on Windows XP. This program displays the status of the system, updates several control parameters, and controls the transporter system. And instead of the Windows timer function, which has a somewhat unpredictable interval, we use a high-precision multimedia timer callback function for greater accuracy and resolution, achieving a control update frequency of up to 1 kHz. This approach is advantageous at the development stage because of the ease of implementation and debugging.

3 REMOTE CONTROL

The master and slave manipulator have kinematically identical structures, and so each pair arms can be controlled by bilateral servo control without any coordinate transformation. For achieving stable and possibly transparent teleoperation, various teleoperation control architectures such as position-position control, position-force control, impedance control, and compliant control have been proposed (Aliaga, Rubio and Sánchez, 2004). However, in our system, because of force/torque sensors cannot be placed on the wrist of the slave manipulator, given the high possibility for sensor failure and difficulties in maintenance, the control architecture is constrained to the use of only motor positions and motor rates. For this reason, we have adopted position-based bilateral force reflection controller based on TDC. TDC uses recent past data to estimate the uncertain dynamics and disturbances in the system. It cancels out the undesired dynamics and disturbances, and substitutes them with the desired dynamics that given in terms of the reference model. The controller design can be performed even if the accurate model was not found. And modeling error has little effect on the controller performance.

3.1 Time Delay Control Law

The dynamic equation of robot manipulator is given by:

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) + D(q,\dot{q}) = \tau \quad (1)$$

where τ is the actuator torque; $q, \dot{q}$ and $\ddot{q}$ denote the joint angle, joint angular velocity, and joint acceleration, respectively. $M(q)$ is the inertia matrix; $C(q,\dot{q})$ is the Coriolis and the centrifugal forces; $G(q)$ is gravity force. $D(q,\dot{q})$ represents the friction and unmodeled nonlinearities. In equation (1), let $M(q)$ be approximated with $\bar{M}(q)$ as a constant matrix, then the equation can be rewritten as

$$\bar{M}\ddot{q} + H(q,\dot{q},\ddot{q}) = \tau \quad (2)$$

$$H(x) = (M - \bar{M})\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + D(q,\dot{q}) \quad (3)$$

Following the idea established by the computed torque control approach, the control input is computed as

$$\tau = \bar{M}\ddot{u} + H(q,\dot{q},\ddot{q}) \quad (4)$$

$$\ddot{u} = \ddot{q}_d + k_v\dot{e} + k_p e \quad (5)$$

where $\ddot{q}_d$ is the desired joint acceleration, $e = q_d - q$, k_v and k_p are the derivative and the proportional gain matrices, respectively. Substituting Equation (4) and (5) into Equation (2), closed-loop error equation can be obtained as follows:

$$\ddot{e} + k_v\dot{e} + k_p e = 0 \quad (6)$$

In the time delay control, it is usually assumed that the value of the uncertainty at present time t is very close to its value at time $t - L$ in past for a very small time delay. Then, $H(t)$ can be estimated as

$$H(t) \approx H(t-L) = \tau(t-L) - \bar{M}\ddot{q}(t-L). \quad (7)$$

Combining equations (4), (5) and (7), the TDC law is obtained as follows:

$$\tau = \tau(t-L) - \bar{M}\ddot{q}(t-L) + \bar{M}(\ddot{q}_d + k_v\dot{e} + k_p e) \quad (8)$$

The structure of the controller is shown in Figure 3.

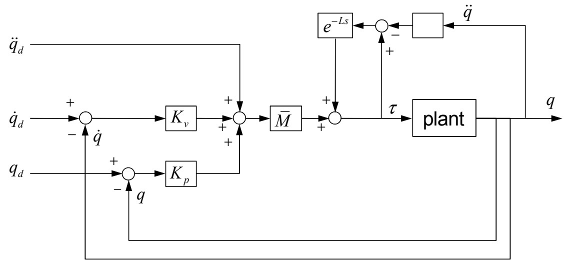


Figure 3: TDC block diagram.

The time delay L is set as the sampling time t of the control system. Two PD-type gains, K_p and K_v, can be determined from an error dynamics which has a desired natural frequency ω_n and a desired damping ratio ζ as

$$k_p = \omega_n^2,\ k_v = 2\zeta\omega_n \quad (9)$$

Step responses of one link arm with variation of ζ and ω_n, are shown in Figure 4 and 5, respectively. Since these responses have typical characteristics of second order system, the tuning procedure of the TDC can be simple and straightforward.

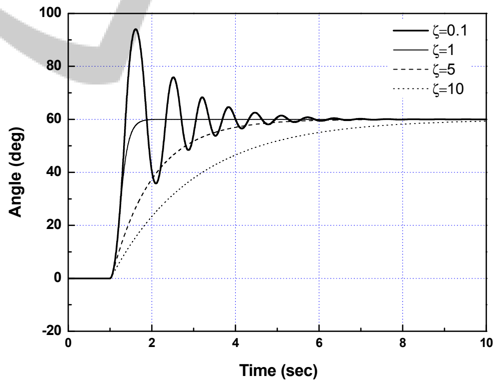


Figure 4: Step responses of various ζ.

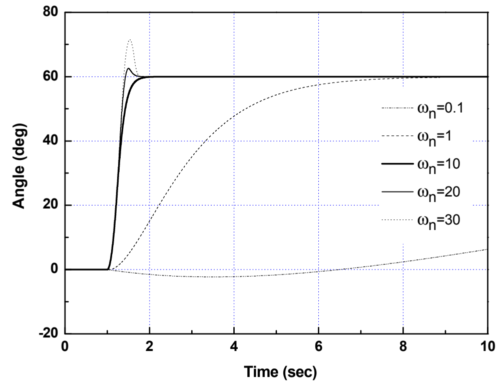


Figure 5: Step responses of various ω_n.

3.2 Controller Design for Master-slave System

The dynamics of master and slave is given by the following equations:

$$\tau_m + f_m = M_m(\theta_m)\ddot{x}_m + C_m(\theta_m, \dot{\theta}_m)\dot{x}_m + G_m(\theta_m) \quad (10)$$

$$\tau_s - f_s = M_s(\theta_s)\ddot{x}_s + C_s(\theta_s, \dot{\theta}_s)\dot{x}_s + G_s(\theta_s) \quad (11)$$

where x_m and x_s denote the position vector of master and slave. M and C represent the inertia matrix and the Coriolis and the centrifugal force respectively. G is the gravity vector. f_m is the force that the operator applies to the master link and f_s denotes the force that the slave arm applied to the object. Actuator driving forces are represented by τ_m and τ_s.

According to the TDC law, Eq.(10) and (11) are rewritten in another form:

$$\tau_m = \tau_m(t-L) - \bar{M}_m\ddot{x}_m(t-L) + \bar{M}_m(\ddot{x}_s + \mathrm{k_{vm}}\dot{e}_m + \mathrm{k_{pm}}e_m) \quad (12)$$

$$\tau_s = \tau_s(t-L) - \bar{M}_s\ddot{x}_s(t-L) + \bar{M}_s(\ddot{x}_m + \mathrm{k_{vs}}\dot{e}_s + \mathrm{k_{ps}}e_s) \quad (13)$$

where $e_m = x_s - x_m$ and $e_s = x_m - x_s$ are position errors of master and slave manipulators. And the closed-loop error equation is

$$\ddot{e}_m + k_{vm}e_m + k_{pm}e_m = 0 \quad (14)$$

$$\ddot{e}_s + k_{vs}e_s + k_{ps}e_s = 0 \quad (15)$$

The structure of the master-slave control system using TDC, is shown in Figure 6. Although it represents simple one DOF model, it can be easily extended to multi-DOF manipulator system since the master-slave system is a replica type which enables to apply a joint-to-joint control.

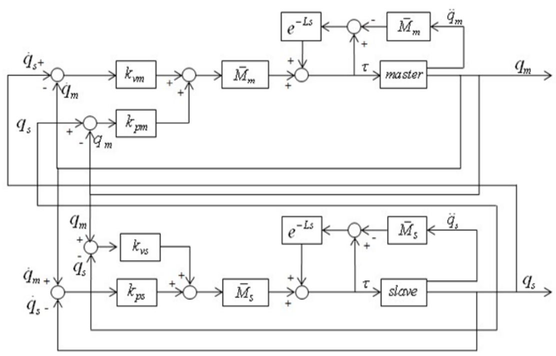


Figure 6: Master-slave control system with TDC.

4 EXPERIMENT

The developed master-slave system was tested to determine its basic operating performance as well as remote handling capability. The angular position of the master-slave system was measured by counting the encoder pulse signals. The angular velocity and the angular acceleration were calculated by numerical differentiation after passing them through a low pass filter.

Figure 7 shows reference trajectory following results with some TDC parameter variations. The natural frequency and damping ratio of desired response are set to be ω_n=10 and ζ=1. $\bar{M}$ in (8) could be selected to satisfy the stability condition (Hsia and Gao, 1990).

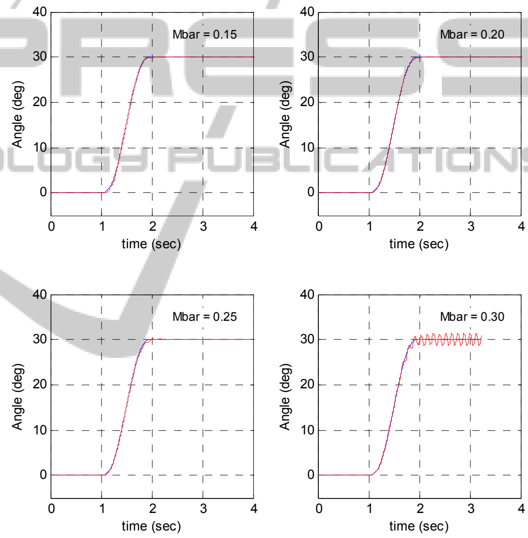
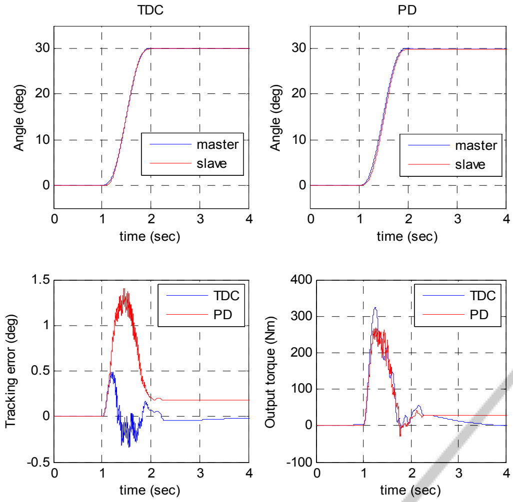


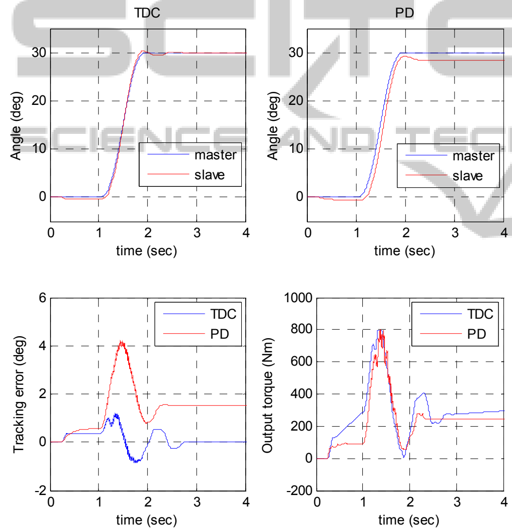
Figure 7: Reference trajectory following results with some parameter variations.

The performances of the system with the TDC are compared with those of the system with the PD. The reference input is designed based on jerk-bounded trajectory planning (Sonja and Elizabeth, 2003) and it applied to both controllers with same values. The gains of two controllers are same in all experiments.

Figure 8 shows experimental results both with a noload and with 25 kgf payload. The system with PD controller has the steady-state error because the controller has fixed gains and it cannot compensate when the load changes or unpredictable disturbances exist. Unlike PD controller, the TDC effectively handles the effect of parameter variations and there are no significant changes in the overall control performance regardless of changes in payloads.



(a) without payload



(b) with a payload of 25 kgf.

Figure 8: Comparison of the performance of PD and TDC.

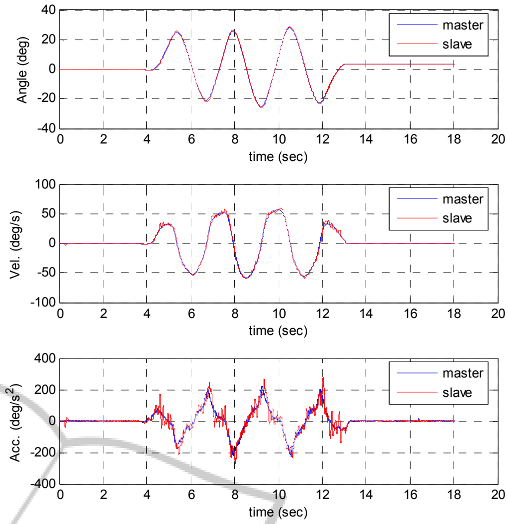


Figure 9: Position tracking results during axis 1 motion where the slave arm with a payload of 10 kgf follows arbitrary motion of the master.

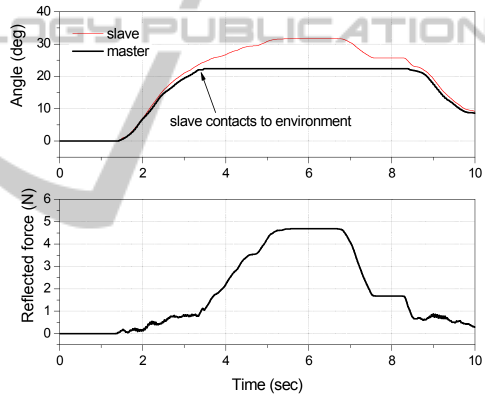


Figure 10: Position-based force reflection.

Figure 9 illustrates a master-to-slave position tracking performances along axis 1 during handling a 10 kgf load. The three tracking indexes—position, velocity, and acceleration—are quite similar across both the master and slave manipulator even though small errors and overshoot exist. However, an operator could deal with these errors without significant degradation since he is located in the teleoperation loop.

Figure 10 shows a force feedback result when a gripper is restricted by an obstacle during master-slave operation. Instead of direct force measurement of the master arm, we calculated the reflected force through measuring the torque acting on its joints. In the figure, we can see that an operator can feel the contact with an environment.

5 CONCLUSIONS

Time delay controller has been successfully implemented for master-slave teleoperation system and its performance was compared with that of the conventional PD controller. From the experimental results, TDC showed good performance in master position tracking in spite of the changes in payload and the force at slave site was effectively reflected to the operator without additional force sensor. Therefore, TDC is an efficient and applicable bilateral force reflection scheme for the master-slave servo-manipulation.

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