Experimental Implementation of Bilateral Teleoperation with Time Delay using Command Governor

Yasunori Kawai and Masayuki Fujita

1Department of Electrical Engineering, Ishikawa National College of Technology, Ishikawa, Japan
(Tel: +81-76-288-8110; E-mail: y.kawai@ishikawa-nct.ac.jp)
2Department of Mechanical and Control Engineering, Tokyo Institute of Technology, Tokyo, Japan

Abstract: This paper considers the implementation of the bilateral teleoperation with time delay using the command governor. The command governor can avoid the constraints violation. However, the command governor is formulated by the quadratic programming, it is hard to solve the problem in the sampling time. In this paper, a algorithm is proposed to decrease the computational cost. In the experiment, the performance of the proposed bilateral teleoperation system is verified using a single-degree of freedom master/slave system.

Keywords: Teleoperation, Time Delay, Constraint

1. INTRODUCTION

Teleoperation consists of a dual robot system called a master robot and a slave robot. For the command of the human operator, the slave robot situated at a remote location tracks the motion of the master robot. In order to improve the task performance, the force feedback from the slave robot to the master robot is needed. In this way, the teleoperation is said to be controlled bilaterally [1].

The master and slave robots are connected to the network in the bilateral teleoperation. The time delay can be imposed in transmission of the data between the master and the slave site. It is known that the time delay in the closed loop system destabilize the stable system. In previous researches, scattering theory and passivity-based control are used to guarantee the stability in case the time delay exists [2].

The teleoperation subject to input/state constraints is considered [3]-[5]. The significance of the method is to add the primal compensated system called command governor (CG). By the CG, the command signals from the human operator are converted into the new signals which satisfy constraints. The CG generates the command signals by solving the convex constrained quadratic optimization problem.

In this paper, the bilateral teleoperation subject to constraints is considered. By using the passivity-based control and the CG, it is indicated that the stability of the bilateral teleoperation is guaranteed. The past research in [6] proved the stability of the bilateral teleoperation by utilizing only the PD-type control law. In [7], the bilateral teleoperation using the CG builds on the architecture derived in [6]. For the command from the master robot often violates the limit of the input of the slave system. The CG which modifies the command to avoid constraint violations, is applied to the bilateral teleoperation. The CG is formulated by the quadratic programming problem. However, it is hard to solve the problem in the sampling time in [7]. This paper proposes a algorithm to decrease the calculation cost. The experimental implementation can be achieved in the sampling time.

The organization of this paper is as follows. The bilateral teleoperation by using the CG is shown Section 2. In Section 3, the stability of the bilateral teleoperation with CG is presented. In Section 4, the comparison between the proposed method and the saturation are illustrated. In Section 5, the experimental results is indicated. Finally, our conclusions are presented.

2. BILATERAL TELEOPERATION WITH COMMAND GOVERNOR

The bilateral teleoperation system based on the PD-type control law using command governor is shown in Fig. 1 [7]. The bilateral teleoperation system is composed of the following parts: the human operator, the master, the slave, the environment and the control parts. The human operator commands the master with force $F_{h}$ to move it with velocity $\dot{x}_{m}$. The position information $x_{m}$ is sent to the slave side. The local controller $F_{feed}$ on the slave side drives the control input that the position $x_{s}$ and the velocity $\dot{x}_{s}$, equal to the position $x_{m}$ and the velocity $\dot{x}_{m}$ of the master. If the slave contacts a remote environment, the force $F_{e}$ affects the position and the velocity of the slave. The local controller $F_{back}$ on the master side gives the control input which decrease the error of the position and the velocity between the master and the slave.

Consider the system

$$M_{m}\ddot{x}_{m} + B_{m}\dot{x}_{m} = F_{h} + F_{back}$$
$$M_{s}\ddot{x}_{s} + B_{s}\dot{x}_{s} = -F_{e} + F_{feed}$$

where $M_{m}$ and $M_{s}$ are inertias and $B_{m}, B_{s}$ represent the master and the slave damping respectively. The local controllers $F_{back}$ and $F_{feed}$ are given by

$$F_{back} = K_{P}(x_{s}(t-T) - x_{m}) + K_{D} (\dot{x}_{s}(t-T) - \dot{x}_{m})$$
$$F_{feed} = K_{P}(g(t) - x_{s}) + K_{D} (\dot{g}(t) - \dot{x}_{s})$$

where $x_{m}(t-T)$ is the delayed master position. The slave side receives the position of the master $T$ [s] ago.
The constraint violations.

It is assumed that the velocity \( \dot{g}(t) \) is provided from the derivative of \( g(t) \) as follows

\[
\dot{g}(t) = \frac{s}{1 + T_N s} g(t).
\]

The control part \( F_{feed} \) can be represented

\[
\dot{x}_{feed} = A_{feed} x_{feed} + B_{feed} (g - x_{s}) \quad \text{and} \quad F_{feed} = C_{feed} x_{feed} + D_{feed} (g - x_{s})
\]

where \( x_{feed} \) is the state, \( g - x_{s} \) is the input, the system matrices \( A_{feed}, B_{feed}, C_{feed}, D_{feed} \) are constant.

The system which consists of using (2) and (6), is derived as

\[
M_s \ddot{x}_s + B_s \dot{x}_s = C_{feed} x_{feed} + D_{feed} (g - x_{s}) - F_e.
\]

The system (7) is rewritten as

\[
\frac{d}{dt} x_s = \begin{bmatrix} 0 & 1 & -\frac{D_{feed}}{M_s} \\ 0 & -\frac{1}{M_s} \\ \frac{0}{M_s} \end{bmatrix} x_s + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} g + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{M_s} \end{bmatrix} F_e \tag{8}
\]

where each parameters are obtained as

\[
A = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{D_{feed}}{M_s} & -\frac{1}{M_s} & \frac{C_{feed}}{M_s} \\ -B_{feed} & 0 & A_{feed} \end{bmatrix}
\]

\[
B_1 = \begin{bmatrix} \frac{D_{feed}}{M_s} \\ B_{feed} \end{bmatrix}
\]

\[
C = \begin{bmatrix} -D_{feed} & 0 & C_{feed} \end{bmatrix}
\]

\[
D_1 = D_{feed}
\]

The continuous system (10), (11) are transformed in discrete time by the sampling time.

\[
x(t+1) = \Phi x(t) + G g(t) + G_d d(t) \tag{12}
\]

\[
c(t) = H_e x(t) + L g(t) + L_d d(t) \tag{13}
\]

The problem is to generate the command \( g(t) \) which satisfies the constraints of the slave

\[
-C_{max} \leq c(t) \leq C_{max}, \quad t = 1, \ldots, m. \tag{14}
\]

The above problem reduces to the following inequality

\[
\begin{bmatrix} A_{ineq} \\ -A_{ineq} \end{bmatrix} g(t) \leq \begin{bmatrix} B_{ineq} \\ -B_{ineq} \end{bmatrix}
\]

where \( A_{ineq} \) and \( B_{ineq} \) are

\[
A_{ineq} = \begin{bmatrix} L & 0 & \cdots & 0 \\ H_c G & \ddots & \vdots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ H_e \Phi^{m-1} G & \cdots & H_e G & L \end{bmatrix}
\]

\[
B_{ineq} = \begin{bmatrix} C_{max} \\ C_{max} \\ \vdots \\ C_{max} \end{bmatrix} - \begin{bmatrix} H_e \\ \vdots \\ \vdots \end{bmatrix} x(0).
\]

In the previous researches, the command governor solve the quadratic problem. However, it is hard to solve the quadratic problem that the command \( g(t) \) which minimizes the position error \( x_m(t - T) - x_s \) is generated in the sampling time of the controller. In order to decrease the computational cost, only the conditions for the constraints are considered. The following algorithm is proposed.

1. Solve the \( g^*(t) \) from the constraint equation \( A_{ineq} g^*(t) = B_{ineq} \).
2. If \( g^*(t) \) satisfies \( |g^*(t)| < |x_m(t - T)| \), then \( g(t) = g^*(t) \), otherwise \( g(t) = g(t) \).

### 3. Stability of Bilateral Teleoperation

The some assumptions are introduced, which is assumed in [1].

- The human operator and the environment can be modeled as passive systems.
- The operator and the environmental force are bounded by known functions of the master and the slave velocities respectively.
- All signals belong to the \( L_{2e} \), the extended \( L_2 \) space.
- The velocities \( \dot{x}_m \) and \( \dot{x}_s \) equal zero for \( t < 0 \).

The position tracking error between the master and the slave robot is defined as

\[
e_s = x_m(t - T) - x_s(t). \tag{16}
\]

**Theorem 1**: Consider the system described by (1)-(4). The master and slave velocities asymptotically converge to the origin and the position tracking error defined by (16) remains bounded.
Thus, the function system is given by

\[ V = \frac{1}{2} (M_m \ddot{x}_m + M_s \ddot{x}_s + K_P (x_m - x_s))^2 + K_D \int_{t-T}^{t} (\ddot{x}_s + \ddot{x}_m) \, dt + \int_{0}^{t} (F_{c} \dot{x}_s - F_h \dot{x}_m) \, dt. \] 

(17)

From the assumptions, the human operator and the remote environment are passive. The following results are obtained

\[ \int_{0}^{t} F_{c} \dot{x}_s \geq 0, \quad - \int_{0}^{t} F_{h} \dot{x}_m \geq 0. \] 

(18)

Thus, the function \( V \) which is proposed in (17) is positive definite. The derivative of (17) along trajectories of the system is given by

\[
\dot{V} = M_m \ddot{x}_m \dot{x}_m + M_s \ddot{x}_s \dot{x}_s + K_P (x_m - x_s) (\dot{x}_m - \dot{x}_s) \]

\[
+ \frac{1}{2} K_D (\ddot{x}_m + \dddot{x}_m) - \frac{1}{2} K_D (\ddot{x}_m (t-T) + \dddot{x}_m (t-T)) \]

\[
+ F_c \dot{x}_s - F_h \dot{x}_m \]

\[
= -B_m \ddot{x}_m - B_s \ddot{x}_s + K_P (x_m (t-T) - x_s) \dot{x}_m \]

\[
+ K_P (x_m (t-T) - x_m) \dot{x}_m \]

\[
- \frac{1}{2} K_D ((\ddot{x}_m - \dot{x}_m (t-T))^2 + (\dddot{x}_m - \dddot{x}_m (t-T))^2) \]

\[
+ K_P (g(t) - x_m (t-T)) \dot{x}_m \dot{x}_s \]

\[
+ K_D (\ddot{x}_m (t-T) - \ddot{x}_m (t-T)) \dot{x}_s \]

(19)

From (4), (16), the following relation is derived as

\[
K_P (g(t) - x_m (t-T)) \dot{x}_s \]

\[
+ K_D (\ddot{x}_m (t-T) - \ddot{x}_m (t-T)) \dot{x}_s \]

\[
= \{K_P (g(t) - x_m (t-T)) + (x_s (t) - x_m (t-T)) \} \dot{x}_s \]

\[
+ \{K_P (g(t) - x_m (t-T)) + (x_s (t) - x_m (t-T)) \} \dot{x}_s \]

\[
= \{K_P (g(t) - x_m (t-T)) + (x_s (t) - x_m (t-T)) \} \dot{x}_s \]

\[
+ \{K_P (g(t) - x_m (t-T)) + (x_s (t) - x_m (t-T)) \} \dot{x}_s \]

\[
= K_P (g(t) - x_m (t-T)) \dot{x}_s \]

\[
+ K_P (g(t) - x_m (t-T)) \dot{x}_s \]

\[
= (F_{feed} - K_P e_s - K_D \dot{e}_s) \dot{x}_s. \] 

(20)

The proof: Define a positive definite function for the system as

\[
\dot{V} = \frac{1}{2} (M_m \ddot{x}_m + M_s \ddot{x}_s + K_P (x_m - x_s))^2 + K_D \int_{t-T}^{t} (\ddot{x}_s + \ddot{x}_m) \, dt + \int_{0}^{t} (F_{c} \dot{x}_s - F_h \dot{x}_m) \, dt. \]

where the notation \( \| - \|_2 \) represents the L2 norm of a signal on the interval \([0, t_f]\). Using Schwartz inequality for any \( \alpha_1 > 0, \alpha_2 > 0 \)

\[
2 \int_{0}^{t_f} \dot{x}_m \int_{0}^{T} \dot{x}_s (t-\tau) \, d\tau \, dt \leq \alpha_1 \| \dot{x}_m \|_2^2 + \frac{T^2}{\alpha_1} \| \ddot{x}_m \|_2^2 \] 

(23)

\[
2 \int_{0}^{t_f} \dot{x}_s \int_{0}^{T} \dot{x}_m (t-\tau) \, d\tau \, dt \leq \alpha_2 \| \dot{x}_s \|_2^2 + \frac{T^2}{\alpha_2} \| \ddot{x}_m \|_2^2. \] 

(24)

It is assumed that

\[
F_{feed} - K_P e_s - K_D \dot{e}_s = -K \dot{x}_s. \] 

(25)

The inequality (22) reduces to

\[
\int_{0}^{t_f} \dot{V} \, dt \leq \left\{ -B_m + K_P \left( \frac{\alpha_1}{2} + \frac{T^2}{2 \alpha_2} \right) \right\} \| \dot{x}_m \|_2^2 \]

\[
+ \left\{ -B_s + K_P \left( \frac{\alpha_2}{2} + \frac{T^2}{2 \alpha_1} \right) \right\} \| \ddot{x}_m \|_2^2 \]

\[- \frac{1}{2} K_D \| \dddot{e}_m \|_2^2 \]

\[- K \| \dddot{e}_m \|_2^2. \] 

(26)

where \( e_m := x_m (t-T) - x_m (t) \). From the equation (25) and the constraint \( -C_{max} \leq F_{feed} \leq C_{max} \), if the constraint \( C_{max} \) satisfies the following relation

\[
-C_{max} \leq -K \dot{x}_s + K_P e_s + K_D \dot{e}_s \leq C_{max} \]

then, the signals \( \dddot{e}_m, \dot{e}_s, x_m - x_s \) are bounded and the signals \( \dddot{e}_s, \dot{e}_s, \dot{e}_s \) converge to zero. Using Barbalat’s Lemma [1], the tracking error defined in (16) can be rewritten as

\[
e_s = x_m (t) - x_s (t) - \int_{t-T}^{t} \dot{x}_m \, dt. \] 

(28)

The position tracking error is bounded.

The above results show that the stability of the teleoperation system with the CG is guaranteed. Compared to the Lyapunov function in [1], the energy with respect to the time delay

\[
K_D \int_{t-T}^{t} (\dddot{x}_s + \dddot{x}_m) \, d\tau \] 

(29)

plays an important role in this approach. In the proposed algorithm in section 2, if \( g^* (t) \) satisfies \( g^* (t) < [x_m (t-T)] \), the stability can be proved as the same as the previous research [7], because \( g(t) = x_m (t-T) \). In the case of \( g(t) = g^* (t) \), the constraint \( C_{max} \) has to be designed satisfying the inequality (27).
4. SIMULATION

In this section, the performance of the bilateral teleoperation proposed in section 3 is verified. The proposed algorithm is compared with the bilateral teleoperation using the saturation of the control input. Consider the single-degree of freedom master/slave robots shown in Fig. 2. The environment is assumed to be a damper system.

![Master/Slave Robot Model](image)

Fig. 2 master/slave robot model

The model parameters are given as \( M_m = 0.0190 \text{ kgm}^2 \), \( M_s = 0.0646 \text{ kgm}^2 \), \( B_m = 0.376 \text{ Nms} \), \( B_s = 0.7696 \text{ Nms} \). The control parameters of the \( F_{\text{feed}} \) and \( F_{\text{back}} \) are designed \( K_P = 5 \), \( K_D = 5 \), \( T_D = 0.1 \), \( N = 10 \), the predictive horizon \( m = 3 \). It is assumed that the constant time delay \( T = 0.5 \text{ s} \) exist and the input of the slave robot is subject to the saturation \( C_{\text{max}} = 0.5 \text{ Nm} \). The simulation results are obtained by using MATLAB.

Figs. 4-7 report the responses under the command governor. The simulation results show that the human operator gives the force \( F_h = 2 \text{ Nm}(t = 1 \text{ s} - 3 \text{ s}) \), the slave robot contacts the environment \( x_s \geq 0.5 \text{ rad} \). Fig. 4 shows that the error of the position \( x_m - x_s \) is bounded. Fig. 5 represents that the signal \( x_m(t-T) \) is modified into the signal \( g(t) \) in order to satisfy the constraints of the control input \( \dot{F}_{\text{feed}} < 0.5 \text{ Nm} \). The signal \( \dot{F}_{\text{feed}} \) is shown in Fig. 6. The proposed bilateral teleoperation indicates that no constraints violation occurs.

![Bilateral Teleoperation with Saturation](image)

Fig. 3 Bilateral Teleoperation with Saturation

The comparison between the proposed command governor and the saturation is considered. The bilateral teleoperation using the saturation is shown in Fig. 3. The saturation part is located between the slave and the local controller of the slave. The saturation part limit the control input as \( \dot{F}_{\text{feed}} \leq 0.5 \). The simulation results are shown in Figs. 8-11. Fig. 9 indicates that the signals \( \dot{F}_{\text{feed}}(t) \) is converted to \( \dot{F}_{\text{feed}}(t) \) when the condition \( \dot{F}_{\text{feed}}(t) > 0.5 \) occurs. It is understand that the proposed CG is better than the saturation for the convergence of the error \( x_m - x_s \).

![Simulation Results](image)

Fig. 4 (CG)Time responses of \( x_m(t) \) and \( x_s(t) \) (solid: \( x_m(t) \), dashed: \( x_s(t) \))

Fig. 5 (CG)Time response of \( x_m(t-T) \) and \( g(t) \) (solid: \( x_m(t-T) \), dashed: \( g(t) \))

Fig. 6 (CG)Time response of \( F_{\text{feed}}(t) \) and \( F_{\text{back}}(t) \) (solid: \( F_{\text{feed}}(t) \), dashed: \( F_{\text{back}}(t) \))

Fig. 7 (CG)Time response of \( F_e(t) \) and \( F_h(t) \) (solid: \( F_e(t) \), dashed: \( F_h(t) \))
5. EXPERIMENTS

The experimental setup consists of two two single degree of freedom actuators and the Digital Signal Processor (DSP) as Fig. 12. The environment at the slave side is the ball which is made by the rubber.

The controllers are implemented on the DSP of the DS1104 (dSPACE). The sample time of the controllers is 1 msec. The force and the position of the master is sent to the DSP through the AD port and the counter port, respectively. At the slave side, the command governor provides the new reference command using the position information of the master \( T \) [s] ago. The control input to track the new reference command is send to the slave through the DA port. As the same as the master, the force and position of the slave is sent to the DSP through the AD port and the counter port, respectively. In order to track the position of the slave, the control input of the master is send to master through DA port at the master side.

The design parameters of the local controllers \( F_{feed} \) and \( F_{back} \) are designed as \( K_P = 4.9, \) \( K_D = 5, \) \( T_D = 0.1, \) \( N = 10. \) The predictive horizon is \( m = 3. \) the constraint is \( C_{max} = 0.5 \) Nm, the time delay \( T = 0.1 \) s. Figs. 13-16 illustrate the time responses. The force \( F_h \) from the human is shown in Fig. 16. From Fig. 16, the slave contacts the environment at time = 9 s. The signal \( x_m(t-T) \) is converted to \( g(t) \) to avoid the constraints violation as Fig. 14. From Fig. 15, \( F_{feed} \) satisfies the constraint 0.5. Fig. 13 indicates that the error of the position \( x_m - x_s \) is bounded. The proposed bilateral teleoperation can be implemented in the sampling time without constraints violation.

![Fig. 12 Experimental Setup](image)

![Fig. 8 (Saturation)Time responses of \( x_m(t) \) and \( x_s(t) \) (solid: \( x_m(t) \), dashed: \( x_s(t) \))](image)

![Fig. 9 (Saturation)Time response of \( x_m(t-T) \) and \( g(t) \) (solid: \( x_m(t-T) \), dashed: \( g(t) \))](image)

![Fig. 10 (Saturation)Time response of \( F_{feed}(t) \) and \( F_{back}(t) \) (solid: \( F_{feed}(t) \), dashed: \( F_{back}(t) \))](image)

![Fig. 11 (Saturation)Time response of \( F_e(t) \) and \( F_h(t) \) (solid: \( F_e(t) \), dashed: \( F_h(t) \))](image)
6. CONCLUSION

This paper considered the constraints in the bilateral teleoperation. The command governor was applied to the bilateral teleoperation, which was formulated by the inequalities constraints. The stability of the bilateral teleoperation utilizing the CG was guaranteed. Using the single-degree-of-freedom master/slave robots, it was shown that the performance of the proposed algorithm was better than the other method in the simulation. The experimental results represent that the proposed method satisfies the constraints using the CG. The proposed algorithms can be implemented in the sampling time.

REFERENCES


