Force Feedback Model of Electro-hydraulic Servo Tele-Operation Robot Based on Velocity Control

Gong Mingde Zhao Dingxuan Feng Shizhu Wei Hailong
College of Mechanical Science and Engineering
Jilin University
Changchun, China
E-mail: gmd@jlu.edu.cn

Hironao Yamada
Department of Mechanical & Systems Engineering,
Gifu University
Gifu, Japan
E-mail: yamada@gifu-u.ac.jp

Abstract—**A tele-operation robotic system using bilateral control is useful for performing restoration in damaged areas, and also in extreme environments such as space, the seabed and deep underground. The system consists of an excavator as the construction robot, and two joysticks for operating the robot from a safe place. Operator needs to feel a realistic sense of task force brought about from a feedback force of the fork glove. A new force feedback model is proposed between fork glove and environments based on velocity control of cylinder to determine environment force acting on fork glove. Namely, the reaction force is formed by the error of displacement of joystick with velocity and driving force of piston, and the gain is calculated by the driving force and threshold driving force. Moreover, the variable gain is developed for grasping soft object. Experimental results are given to demonstrate the proposed algorithm has good stability and transparency for grasping soft object.**

Keywords—**Tele-operation, Bilateral electro-hydraulic servo control, Velocity control, Force feedback model**

Ⅰ. INTRODUCTION

A tele-operation robotic system using bilateral control is useful for performing restoration in damaged areas, and also in extreme environments such as space, the seabed, and deep underground [1]. The world's first remote control system was a mechanical master-slave manipulator called ANL Model M1 developed by Goertz [2]. Since its introduction, the field of tele-operation has expanded its scope. Its use has also been demonstrated in space, construction, forestry, and mining. As an advanced form of tele-operation, the concept of "tele-presence" was proposed by Minsky [3]. Tele-presence enables a human operator to remotely perform tasks with dexterity, providing the user with the feeling that she/he is present in the remote location. About the same time, "tele-existence", a similar concept, was proposed by Tachi [4].

As an application for excavator control, bilateral matched-impedance tele-operation was developed at the University of British Columbia [5, 6]. They also have developed a virtual excavator simulator suitable for experimentation with user interfaces, control strategies, and operator training [7]. This simulator comprises machine dynamics as an impedance model, a ground-bucket interaction model, and a graphical display sub-system.

In order to improve the controllability of the system, we examined the master and slave control method between joysticks and robot arms [8], [8] discussed the force presentation of the task field for an operator. In those studies mainly focused on position control of master-slave side and developed force feedback models. Namely, the operator controls the displacement of piston of slave side by the displacement of joystick. These methods can realize highly sensual force feedback to joystick [8]. But the strange sensing will be felt when the operator moved the joystick using position-position control. Many operators get used to position-velocity control. After that, we apply this normal method that the operator controls the velocity of piston of slave side by the displacement of joystick because this method is a standard practice for bilateral control. Moreover, the new force feedback model is developed. Experimental results for one degree-of-freedom are given to demonstrate the proposed algorithm has good stability and transparency for both grasping flexible and rigid object.

Ⅱ. NOMENCLATURE

b_m	: Damp of joystick	[Ns/m]
f_s	: Driving force to slave	[N]
$G(s)$	: Transfer function of joystick (Input: torque to joystick and output: displacement of joystick)	
K_m	: Steady-state value of master	[N^{-1}]
k_{pm}	: Proportional gains of master	[Nm]
k_{tm}	: Torque gain of master	[Nm]
L_m	: Delay time of joystick	[s]
T_m	: Time constant of master	[s]
T_r	: Nondimensional quantity of τ_r ($=\tau_r/\tau_{0r}$)	[-]
y_m, y_s	: Displacements of master and slave	[m]
v	: Velocity of piston	[m/s]
y_{0m}	: Nominal quantity of y_m (y_{0m}=0.06)	[m]
v_{0m}	: Nominal quantity of v_m (v_{0m}=0.10)	[m/s]
Y_m	: Nondimensional quantity of y_m (=y_m/y_{0m})	[-]
V_s	: Nondimensional quantity of v (=v_m/v_{0m})	[-]
y_{0s}	: Nominal quantity of y_s (y_{0s}=0.3)	[m]
Y_s	: Nondimensional quantity of y_s (=y_s/y_{0s})	[-]
τ_m	: Input torque to joystick	[Nm]
τ_r	: Reaction torque to joystick	[Nm]

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Ⅲ. CONSTRUCTION ROBOT SYSTEM AND MATHEMATICAL MODEL OF MASTER SIDE

Experimental apparatus consists of the joystick and the tele-operated construction robot. The joystick can be operated to the X- and Y-axis directions. The hydraulic cylinders for driving the construction robot are controlled by the servo valves. The displacements of the cylinders are detected by magnetic stroke sensors which are embedded in the pistons. The external forces to which the cylinders respond are detected by a pair of pressure sensors attach to the cylinders.

In order to get the mathematical model of the master system, we practiced a parameter identification of the joystick. The identification result shows a step response curve of the displacement y_m to the input torque of the joystick. From this result, the transfer function of the joystick was estimated as the one of the first order lag system (T_m=0.125 s, K_m=0.18 N^{-1}) with a time lag element (L_m =0.08 s). Transfer function of joystick is just as the following equation（1）.

$$G(s) = \frac{K_m s}{T_m s + 1} e^{-L_m s} \quad (1)$$

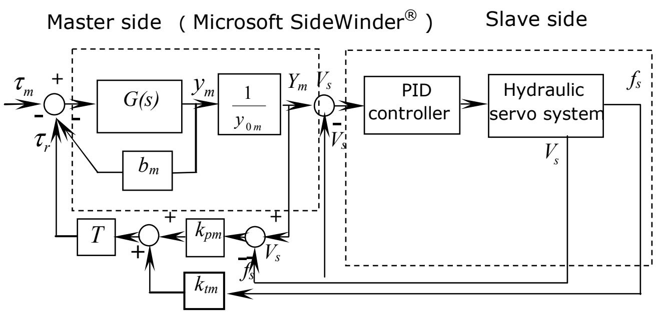


Figure 1 Schematic diagram of master-slave system of force feed back model based on velocity control

Ⅳ. FORCE FEEDBACK MODEL BASED VELOCITY CONTROL

1 Constant threshold driving force feedback model

The difference of velocity control method is that the feedback value is the non-dimensional value of velocity of piston instead of the non-dimensional value of displacement of piston. The position of joystick reaches middle position (zero position), the velocity of piston equals to zero. The more large displacement of joystick is, the more large velocity of piston is. The controller is PD controller. The block diagram for representing the control method is illustrated in Fig. 1 The reaction torque and the gain to the joystick τ_r is given by Eq. (2) and (3).

$$\tau_r = T\{k_{pm}(Y_m - V_s) + k_{tm} f_s\} \quad (2)$$

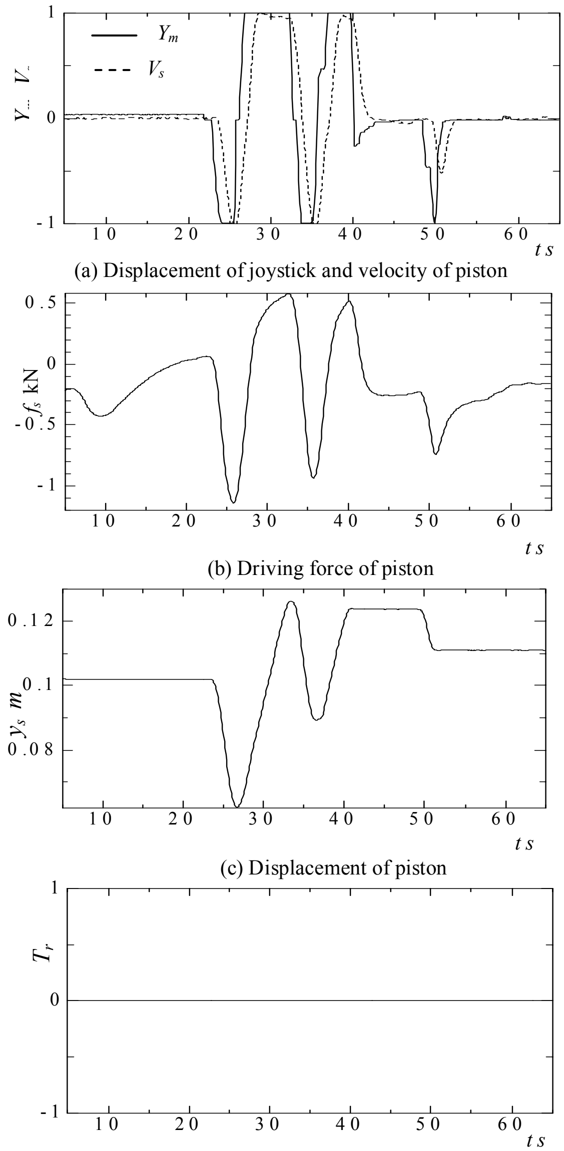
$$T = \begin{cases} 0 & (f_e \le f \le f_c) \\ 0 < \dfrac{f - f_e}{f_{e\_max} - f_e} < 1 & (f < f_e) \\ 0 < \dfrac{f - f_c}{f_{c\_max} - f_c} < 1 & (f > f_c) \end{cases} \quad (3)$$

In Eq. (3), the parameters f_e/f_c that is summation of friction, inertial force and weight of piston are called expanding/contracting motions threshold driving forces. The value cannot be got easily and be regarded as constant value in this research, which is when an external force generated for grasping a task object by the fork glove is absent (f_e=2.0 kN, f_c=-1.4 kN). Furthermore, the maximum driving force to the cylinder in expanding and contracting motions are denoted as f_{e_max} and f_{c_max} (f_{e_max} =11.7kN, f_{c_max} = -6.8kN).

The experimental results which move the joystick in free space namely without grasping object are following Fig. 2. In the Fig. 2 (a) the solid line is the displacement of joystick and the broken line is the velocity of piston. We can find the error of two lines is very small. It can be inferred from Eq. (2) and Eq. (3), the Fig. 2 (b) shows the driving force is in the range of threshold driving forces and T equal to zero. The reaction force to joystick equals to zero. From the experimental results, when the external force is absent in the fork glove, the joystick becomes smooth because the reaction force to joystick is zero. We can find the result from Fig. 2 (d), the actual force information of slave side can be felt well to operator.

When the fork glove grasp soft object step by step especially, under slow speed, the experimental results moving the joystick to grasp soft object are following Fig. 3. In the Fig. 3 (a) the A part, not move the joystick; in the B part, move the joystick to grasp the tire; in the C part, grasping the tire, and in the D part, unlock the tire. The Fig. 3 (b) shows the driving force is not in the range of threshold driving forces and T does not equal to zero. The reaction force to joystick is not zero. From the experimental results, we can find the result from Fig. 3 (d), in the C part, operator can feel reaction force but it is so small that operator did not feel the actual force step by step to fork glove. When the external force is exist and changes slowly in the fork glove, the actual force information of slave side cannot be felt well to operator.

The mainly reason is that the driving force f_s does not necessarily exceeds the region of $f_c \le f_s \le f_e$. This unsatisfactory situation occurs in a task when the fork glove grasps a soft object in a slow velocity. First, displacements of the joystick and velocity of the fork glove piston, Y_m and V_s, are shown in Fig. 3 against time t in the abscissa. The short vertical line marked in the figure indicates the starting point of the task. After starting the part C, as shown in the figure, the task of grasping the tire continues in this manner that the displacement of piston reach grasping maximal position and unlock it step by step and then, at about 90s, the tire is crushed completely. From the driving force and reaction force figure, it is observed that the driving force and reaction is also maximal. But in the picture of the driving force to the fork glove f_s is shown in Fig. 3 (b). The broken lines in the figure denote the threshold driving forces f_e, f_c. As seen in the figure, the driving force f_s is in range of threshold driving forces $f_c \le f_s \le f_e$, when the driving force is small at begin of grasping. In the Eq. (2) and (3), the gain T equals to zero, and the reaction force T_r to joystick is also equals to zero. Therefore the proposed algorithm is not feedback the factual force to fork glove. In this study, we focus on such a problem as seen here and aim at overcoming the problem using velocity control method.



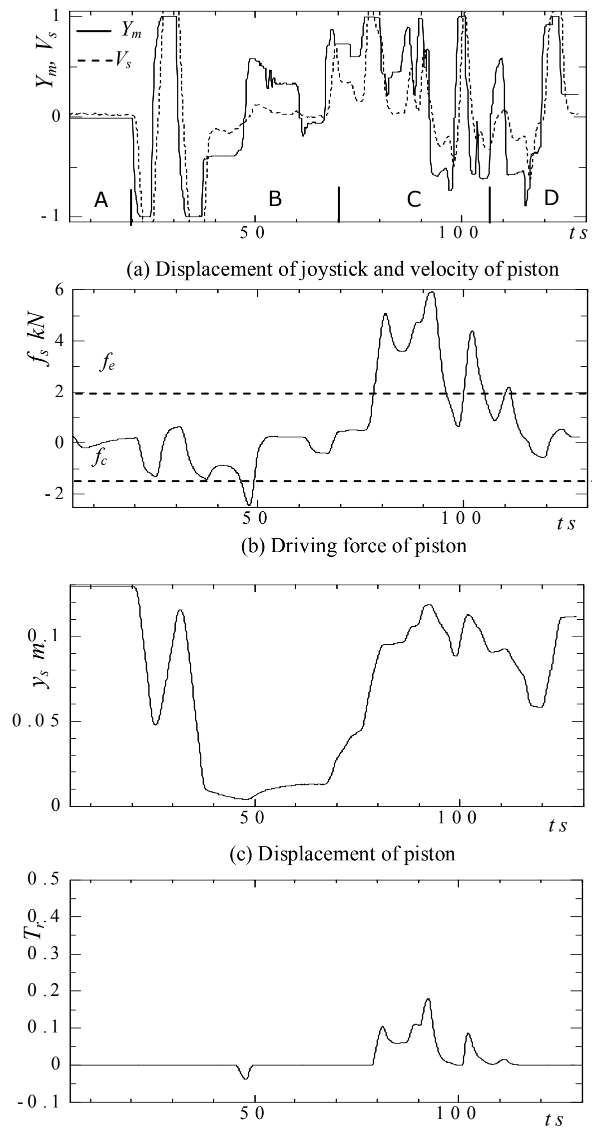
(a) Displacement of joystick and velocity of piston

(b) Driving force of piston

(c) Displacement of piston

(d) Reaction force to joystick

Figure 2 Move joystick in free space



(a) Displacement of joystick and velocity of piston

(b) Driving force of piston

(c) Displacement of piston

(d) Reaction force to joystick

Figure 3 Grasping a tire with constant threshold value

This problem is considered to be originated from the next reasons. In the control method based on Eq. (3), each value of threshold driving forces f_e, f_c is treated as constant. For this reason, the reaction torque T_r can appear as seen in Fig. 3 only when the driving force of the fork glove f_s exceeds the threshold f_e as seen in Fig. 3. On the other hand, in the region of $f_c \le f_s \le f_e$, since the gain T becomes zero in this situation, the reaction force does not appear despite that the fork glove is grasping a task object.

2 Improved threshold driving force feed back model

As well known, the driving force f_s is indicated as a function of the velocity v. Consequently it is better to adopt a variable threshold driving force changing with the velocity v, instead of fixed thresholds f_e, f_c. In the improved method, therefore, we adopt the variable threshold f_{pre}. As a experimental result, the threshold f_{pre} is described by Eq. (4).

$$\begin{cases} f_{prep} = (35.7v^2 + 25.5v + 0.4) \times 10^3 ; (v \ge 0) \\ f_{prep} = (-19.8v^2 + 5.6v - 0.4) \times 10^3 ; (v < 0) \end{cases} \tag{4}$$

By applying Eq. (4), it is expected that the new method is able to deal with a grasping motion of time dependence, e.g. slow-moving grasping, and also to feed back sensitively a reaction force of an external force, moreover increasing maneuverability through controlling velocity of piston.

The reaction force to joysticks τ_r is as shown in Eq. (5), described by the relation depending on the difference between the displacement of joystick and the velocity of piston also the driving force. At the same time, we also don't consider the inertia force and friction of piston. As a consequence, the reaction force to joystick τ_r of the improved algorithm is written by Eq. (5) and the gain T is determined by Eq. (6).

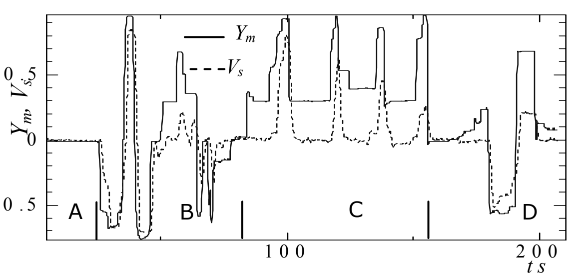
$$\tau_r = T\{k_{pm}(Y_m - V_s) + k_{tm} f_s\} \tag{5}$$

$$T=\begin{cases}0 & (|f_s|\le|f_{pre}|)\\ 0<\dfrac{f_s-f_{pre}}{f_{e\_\max}-f_{pre}}\le 1 & (f_s>0\ \cap\ f_s>f_{pre})\\ 0<\dfrac{f_s-f_{pre}}{f_{c\_\max}-f_{pre}}\le 1 & (f_s<0\ \cap\ f_s<f_{pre})\end{cases}\qquad(6)$$

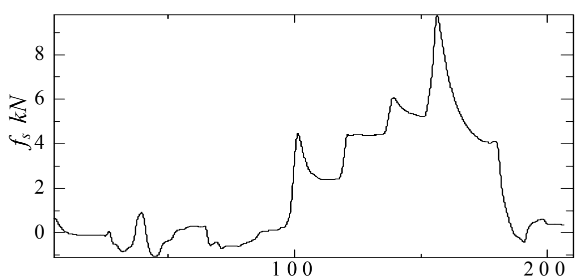
As shown in Eq. (6), the gain T changes its value with the change in the driving force threshold f_{pre}. Iif the driving force to piston f_s is bigger than the threshold f_{pre} given by Eq. (6), the difference between them is regarded as the external force to the piston, and thus the corresponding reaction force can be generated. It is therefore expected in this method that the operator can feel the grasping force to he fork glove very well, even if it is doing a slow-move in grasping of soft object.

In Fig. 4, a task of grasping a tire step by step with slow velocity was tested by the velocity control method. In Fig. 4 (a) the A part, not move the joystick; in the B part; move the joystick to grasp the tire; in the C part, grasping the tire, and in the D part, unlock the tire.

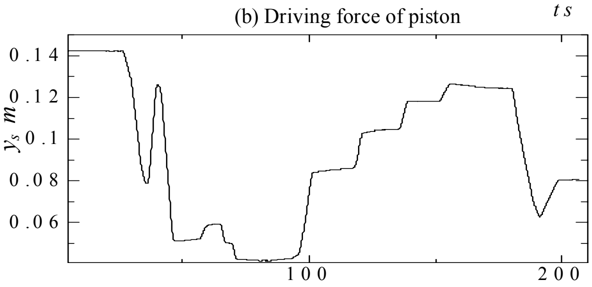
After starting the part C, operator can feel reaction force very well, the task of grasping the tire continues in this manner that the displacement of piston reach grasping the tire step by step and then, at about 155s, the tire is crushed completely. In Fig. 4 (a) the C part, it is observed that following the increase the displacement of piston controlled by joystick, the velocity of piston is decrease step by step. At the same position of joystick, the velocity of piston is difference.



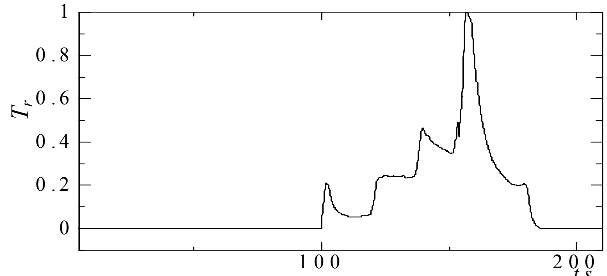
(a) Displacement of joystick and velocity of piston



(b) Driving force of piston



(c) Displacement of piston



(d) Reaction force to joystick

Figure 4 Grasping a tire with variable threshold value

So the reaction force to joystick is difference. From the driving force and reaction force figure, at about 155s, it is observed that the driving force and reaction is also maximal. In the course of grasping task, as the curve of the reaction force to the joystick T_r is shown in the Figure 4 (d), it is observed that the reaction force T_r is appearing in C part, and the reaction force to joystick is also increase step by step. As shown in Fig.4 (d), in the C part, operator can feel the change of reaction force step by step, on the other hand, operator cannot feel reaction force in other parts. That is the same as the actual external force to fork glove. The reaction force T_r is prominence in comparison with Fig.3, we can find that the improved method get satisfy results. The experimental results shown the improved algorithm has good transparency for slave side force and advances the maneuverability of system.

Ⅴ. CONCLUSIONS

In a tele-robotic hydraulic construction robot system, the operator needs to feel a realistic sense of task force which is brought about from a feedback force of the fork glove. Based on velocity control, we proposed a novel control method named as the variable-gain velocity control. This method can obtain the sensitivity force feedback to operator. Namely, the operator is able to feel a realistic sense of the task force when he was grasping a soft object in comparatively a slow velocity.

Based on velocity control, a novel force feedback model is proposed. The experimental results shown the availability of the improved algorithm was confirmed.

REFERENCES

[1] Special Issue: Unmanned Construction to Become Familiar, Nikkei Construction, 2002,296: 38~56 (Nikkei Business Publications Inc., Archive CD-ROM2002, No.155490)

[2] Goertz, R. C.. Fundamentals of General-Purpose Remote Manipulators, Nucleonics, 1952,10-11: 36~42

[3] Minsky, M.. Telepresence, Omni. New York, NY, 1980, Omni Publications International Ltd.

[4] Tachi, S., Maeda, T. Yanagida, Y., Koyanagi, M., Yokoyama, Y.. A method of mutual tele-existence in a virtual environment, Proceedings of the ICAT, 1996, 9~18

[5] S. Tafazoli, P. D. Lawrence, S. E. Salcudean. Identification of Inertial and Friction Parameters for Excavator Arms, IEEE Tr. on Robotics and Automation, 1999, 15(5): 966~971.

[6] S.E. Salcudean, K. Hashtrudi-Zaad, S. Tafazoli, S.P. DiMaio, C. Reboulet. Bilateral Matched-Impedance Teleoperation with Applications to Excavator Control. Control Systems Magazine, 1999, 19(6): 29~37.

[7] S.P. DiMaio, S.E. Salcudean, C. Reboulet, S. Tafazoli, K. Hashtrudi-Zaad. A Virtual Excavator for Controller Development and Evaluation. IEEE International Conference on Robotics and Automation, Belgium, 1998, Vol.1: 52~58

[8] Y. Yokokohji. Control Theory of Master-slave System, JRSJ, 1993, 11(6): 26~34