

EXPERIMENTAL STUDY ON HYDRAULIC SIGNAL COMPENSATION FOR THE APPLICATION OF A HAPTIC INTERFACE TO A TELE-OPERATED EXCAVATOR

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ABSTRACT: Excavators are widely used in public works and construction sites. Semi-automated or automated excavators are also being developed. They are used for very dangerous tasks such as building dismantlement and disaster restoration. Under difficult circumstances, it is more efficient to use an excavator operated with a remote control system. Many researches are underway to develop this kind of system. Conventional remote control systems have been mostly dependent on two-dimensional images. In this study, this system was used, which made it difficult to measure the depth of the excavation location and it took a long time to complete the work. That is why there have not been many practical cases of utilization of tele-operated excavators. Because of these limitations, the haptic technology is proposed that enables recognition of bucket-reflected force and its passing on to the operator. The research was conducted to overcome these difficulties of using two-dimensional images, by developing a force-feedback joystick that efficiently detects the underground condition and applies it to a tele-operated excavator.

Keywords: *Tele-Operated Excavator, Haptic Interface, Force-feedback Joystick, Hydraulic Signal, Regression Matrix*

1. INTRODUCTION

With customer needs diversifying in the domestic construction industry, infrastructure is becoming advanced, complicated, and high-quality. Thus, it is very important to have improved technology amidst the competition. Also, because of the opening of the construction industry, the goal of construction companies to increase their competitiveness is to become high-value-added businesses through technology. Since the construction industry is regarded as a 3D (Dirty, Difficult, and Dangerous) industry, however, and as such, young people avoid working in it, it is becoming more difficult to secure skilled workers for it.

The domestic construction industry should solve problems such as lack of skilled workers, saturation of aging workers, safety matters, and weakened competitiveness of construction technology. These problems can be addressed by “Construction Automation”. Construction automation means software engineering such

as informatization using technologies for computer utilization, management systems, and hardware engineering, which refers to automatic and semi-automatic robot development for mechanization [1]. There are limits not only to operating construction equipment in dangerous places such as slopes, soft ground, building dismantling sites, distressed areas, and construction waste landfills, but also to working in these places, because operators can be exposed there to dangerous environments. Therefore, construction automation is definitely needed for the safe use of construction equipment.

Excavators are widely used in public works and construction sites. They are particularly used for very dangerous tasks such as building dismantling and disaster restoration. Under difficult circumstances, it is more efficient to use an excavator operated with a remote control system. The conventional tele-operated excavator system, however, has been mostly dependent on two-dimensional

images. If it is used, it would be difficult to measure the depth of the excavation location, and it will take a long time to complete the work. To solve these problems, the haptic technology is proposed, which allows recognition of bucket-reflected force and its pass it to the operator.

Haptics is a generic term for the study of the use of remote controls and robots to deliver sense-of-touch information to operators in remote places. To send various and accurate information on virtual objects to operators, the precise implementation of touch is needed [2]. Haptic interface, one of the fields of study in haptics, makes operators feel as if they are in an actual or virtual environment through a haptic device [3]. A joystick is used with a thumb and an index finger, and is most sensitive to humans, so it is a very appropriate haptic device [4].

Therefore, this research was conducted to develop a force-feedback joystick that can efficiently detect the underground condition and realize the reflected forces using hydraulic signal compensation to allow the application of a force-feedback joystick to a tele-operated excavator so as to overcome the difficulties of using two-dimensional images in tele-operated excavators.

2. IMPLEMENTATION OF THE MASTER SYSTEM

A. Configuration of the Force-Feedback Joystick

Although the excavator has a control lever with greater than 6DOF, usually less than 2-3 actuators move at the same time in a movement of the unit, so the force-feedback joystick can have 2DOF. A force-feedback joystick consists of three major components: the transmission mechanism, the actuator, and the sensor. Among these components, the transmission mechanism determines the workspace of the joystick. In general, the transmission mechanism can be classified into the coupled type and the decoupled type. The single-yoke type under the coupled type has the advantage of a simple structure, as shown in Fig. 1 (a). When the central yoke moves, however, it has the disadvantage of its two semi-circular connectors interfering with each other [5]. To remove a contact, cancel and mitigate the interference, and reduce the friction between the semi-circular connectors, the multi-yoke type transmission mechanism was adopted, as shown in Fig. 1 (b).

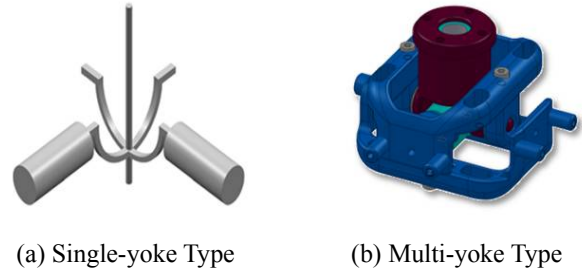


Fig. 1 Type of transmission mechanism.

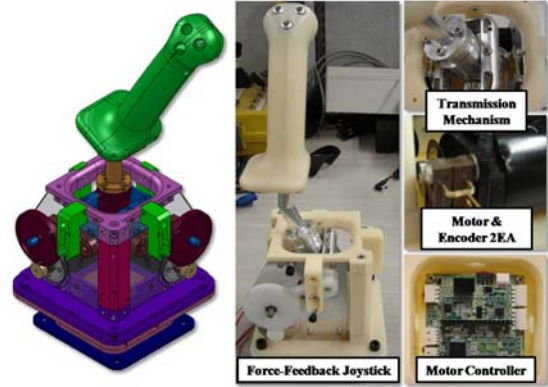


Fig. 2 Configuration of the developed force-feedback joystick.

In this study, two DC motors were used, as shown in Fig. 2, to derive the reflected forces. A gear structure using compound gearing was adopted for torque amplification. An encoder was used to produce a servo motor, and each axis had one potentiometer for initial position control.

B. Kinematic Analysis of the Force-Feedback Joystick

The reference and rotated coordinates of the force-feedback joystick are shown in Fig. 3, and the constraints of the lever are defined as follows:

$$\begin{cases} l_1 = 95 [mm], l_2 = 45.24 [mm] \\ l_3 = 146 [mm], l_4 = 137.34 [mm] \end{cases} \quad (1)$$

If the length from the reference coordinate to the end-point of the joystick is r , the end-point of the joystick is represented by α , β , and r of the spherical coordinate. From Eq. (1), r is derived as follows:

$$r = \sqrt{l_3^2 + l_4^2 - 2l_3l_4 \cos 156^\circ} = 277.15 [mm] \quad (2)$$

The spherical coordinate can be mapped on the Cartesian coordinate system represented by x , y , and z , as follows:

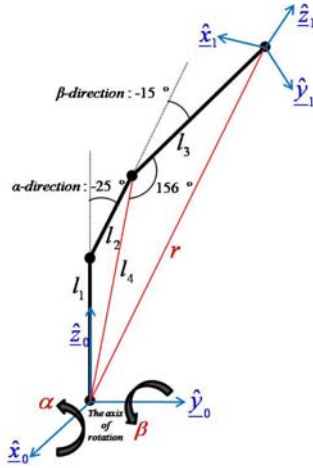


Fig. 3 Schematic of the joystick's lever.

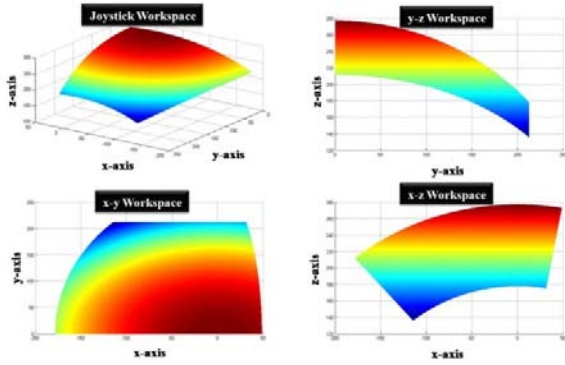


Fig. 4 Workspace of the force-feedback joystick.

$$\begin{aligned} x &= rc(\alpha - 25^\circ)s(\beta - 25^\circ) \\ y &= -rs(\alpha - 25^\circ) \\ z &= rc(\alpha - 25^\circ)c(\beta - 25^\circ) \end{aligned} \quad (3)$$

The workspace of the force-feedback joystick can be obtained using Eq. (3), and is shown in Fig. 4 with the constraints $-25^\circ \leq \alpha, \beta \leq 25^\circ$, and r [6].

To verify singularity in the workspace of the joystick, the 3×3 Jacobian matrix can be calculated using partial derivatives with independent variables (α , β , and r). The determinant of the Jacobian is derived as follows:

$$\det J = r^2 \cos(\alpha - 25^\circ) \quad (4)$$

The singularity angles of the joystick can be derived from Eq. (4). Singularities occur at $\alpha = -65^\circ$ or 115° , which are out of the constraints. Therefore, in this study, there was no need to consider singularity problems of the force-feedback joystick.

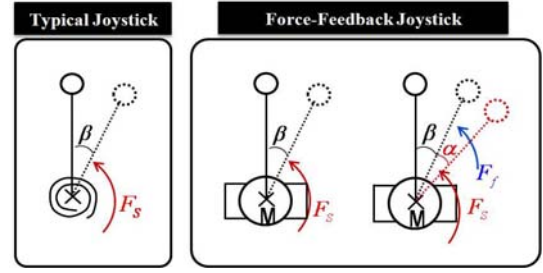


Fig. 5 Comparison of the typical joystick and the force-feedback joystick.

C. Control Algorithm of the Force-Feedback Joystick

The joystick has to go back to its initial position to minimize the load of the motor and to prevent the motor's malfunction if its operator does not use a joystick. Also, to make operators feel the same tension that they would feel if they were using a real joystick, a control algorithm was applied, as follows.

The force-feedback joystick that was applied in this study assumes the role of the spring in a general joystick using a DC motor, as shown in Fig. 5 (a). As mentioned that the joystick has to return to its initial position, if the angle of the joystick is defined as β , Eq. (5) is derived as follows:

$$\beta_{ref} = 0^\circ, e = -\beta \quad (5)$$

Through the gain of the PD control, the spring and damping term of the joystick can be derived as follows:

$$F_s = K_p e + K_d \dot{e} = -K_p \beta - K_d \dot{\beta} \quad (6)$$

The operator can change the tension of the joystick as he or she desires by changing each gain in Eq. (6). Also, when the slave system contacts an environment, the virtual position error of the end-effector is defined as e_v , and the total force that operators receive is defined as F ; and the following equations are derived from Fig. 5 (b):

$$\begin{aligned} e_v &= -\alpha \\ F &= F_s + F_f \end{aligned} \quad (7)$$

In Eq. (7), F_f means the reflected force when the end-effector contacts an environment. Therefore, F_f can be written as $K_f e_v$. If K_f has the same value as the P gain, F in Eq. (7) is derived as follows:

$$\begin{aligned}
F &= -K_p\beta - K_d\dot{\beta} - K_f\alpha \\
&= -K_p(\alpha + \beta) - K_d\dot{\beta}
\end{aligned} \tag{8}$$

Therefore, the operator can get information on the environment through the proper gain tuning of the PD control.

3. COMPENSATION FOR HYDRAULIC SIGNALS

Before the force-feedback joystick was applied to an electronic excavator, it was necessary to find a solution for transmitting the reflected forces to the force-feedback joystick. Since an F/T sensor cannot be attached to the bucket of the excavator, it is expected to realize reflected forces by obtaining hydraulic signals of the boom, arm, and bucket cylinder from an electronic excavator. Hydraulic signals are obtained when the excavator arms move freely. As the reflected force must be transmitted to the joystick only when it makes contact with the environment, a dynamic analysis of the excavator arms is needed to compensate for the hydraulic signals with free motion. Because the dynamic parameters of the excavator arms are unknown, however, the reflected force is realized in a way that estimates the dynamic parameters using a regression matrix, calculates the torque of each joint using the estimated dynamic parameters, and compares it with real hydraulic signals.

A. Dynamic Equation of the Excavator Arms

When the dynamic model of a rigid-link manipulator is expressed symbolically, the dynamic equation can be written as follows:

$$H(q)\ddot{q} + C(q, \dot{q}) + G(q) = \tau \tag{9}$$

wherein $H(q)$ is the $n \times n$ inertia matrix of the manipulator, $C(q, \dot{q})$ is an $n \times 1$ vector of the centrifugal and Coriolis terms, and $G(q)$ is an $n \times 1$ vector of the gravity terms. Also, q is a joint-variable vector and τ is a joint-torque vector.

Fig. 6 shows a schematic of the excavator arms with the assigned variables q_1 , q_2 , and q_3 for the boom, arm, and bucket joint angles, respectively. The swing angle is not considered in this study. In Fig. 6, G_i is the center of gravity for link, which is expressed in the polar coordinates (r_i, α_i) relative to link i [7].

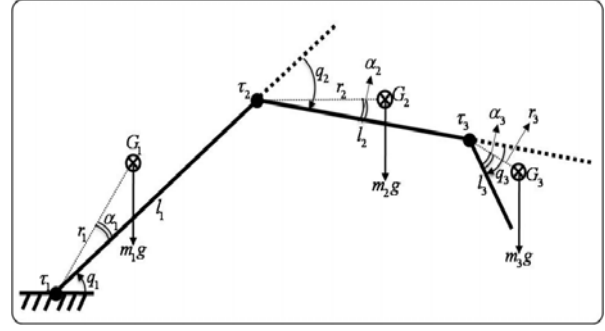


Fig. 6 Schematic drawing of the excavator arms.

If the system is conservative and the excavator's cabin does not move, the dynamic equation using the Lagrange method is derived as follows:

$$\begin{aligned}
\tau_3 &= (I_3 + m_3 r_3^2) \ddot{q}_{123} + m_3 l_1 r_3 \left[\ddot{q}_1 c(q_{23} + \alpha_3) + \dot{q}_1^2 s(q_{23} + \alpha_3) \right] \\
&\quad + m_3 l_2 r_3 \left[\ddot{q}_2 c(q_3 + \alpha_3) + \dot{q}_2^2 s(q_3 + \alpha_3) \right] \\
&\quad + m_3 g r_3 c(q_{123} + \alpha_3) \\
\tau_2 &= \tau_3 + (I_2 + m_2 r_2^2 + m_3 l_2^2) \ddot{q}_{12} + m_3 l_1 l_2 (\ddot{q}_1 c_2 + \dot{q}_1^2 s_2) \\
&\quad + m_3 l_2 r_3 \left[\ddot{q}_{123} c(q_3 + \alpha_3) - \dot{q}_{123}^2 s(q_3 + \alpha_3) \right] \\
&\quad + m_2 l_1 r_2 \left[\ddot{q}_1 c(q_2 + \alpha_2) + \dot{q}_1^2 s(q_2 + \alpha_2) \right] \\
&\quad + m_3 g l_2 c_{12} + m_2 g r_2 c(q_{12} + \alpha_2) \\
\tau_1 &= \tau_2 + \left[I_1 + m_1 r_1^2 + (m_2 + m_3) l_1^2 \right] \ddot{q}_1 \\
&\quad + m_2 l_1 r_2 \left[\ddot{q}_2 c(q_2 + \alpha_2) + \dot{q}_2^2 s(q_2 + \alpha_2) \right] \\
&\quad + m_3 l_1 l_2 (\ddot{q}_2 c_2 - \dot{q}_2^2 s_2) \\
&\quad + m_3 l_1 r_3 \left[\ddot{q}_{123} c(q_{23} + \alpha_3) - \dot{q}_{123}^2 s(q_{23} + \alpha_3) \right] \\
&\quad + (m_2 + m_3) g l_1 c_1 + m_1 g r_1 c(q_1 + \alpha_1)
\end{aligned} \tag{10}$$

wherein I_i is the moment of inertia of each link (boom, arm, and bucket), $q_{12} = q_1 + q_2$, $q_{23} = q_2 + q_3$, and so on.

B. Identification of the Dynamic Parameters Using a Regression Matrix

As mentioned, the dynamic parameter of the excavator arms is unknown. To identify the dynamic parameters of the excavator arms, Eq. (9) can be converted into the linear representation of the dynamic model in the reference [8], as follows:

$$u = Y(q, \dot{q}, \ddot{q})\rho \tag{11}$$

wherein u is the joint-torque vector, ρ is the unknown constant parameters vector, and Y is the regression matrix.

If the joint torques, angles, velocities, and accelerations have been obtained at the given time instances $t_i (i = 1, \dots, n)$, Eq. (11) can be rewritten as follows:

$$u = \begin{bmatrix} \tau(t_1) \\ \tau(t_2) \\ \vdots \\ \tau(t_n) \end{bmatrix} = \begin{bmatrix} Y(t_1) \\ Y(t_2) \\ \vdots \\ Y(t_n) \end{bmatrix} \rho \quad (12)$$

The left pseudo-inverse matrix of Y can be applied to the previous equation. Then a least squares estimate can be found as follows:

$$\rho = (Y^T Y)^{-1} Y^T u \quad (13)$$

When the excavator works in a real field, the velocities and accelerations of the excavator arms are slow. Therefore, the velocities and accelerations were not considered in this study, and Eq. (11) can be rewritten as follows:

$$\begin{bmatrix} gc_1 & -gs_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & gc_{12} & -gc_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & gc_{123} & -gs_{123} \end{bmatrix} \rho_G = \begin{bmatrix} \tau_1 - \tau_2 \\ \tau_2 - \tau_3 \\ \tau_3 \end{bmatrix} \quad (14)$$

wherein the unknown dynamic parameters vector (ρ_G) is derived as follows:

$$\rho_G = \begin{bmatrix} (m_2 + m_3)l_1 + m_1 r_1 c \alpha_1 \\ m_1 r_1 s \alpha_1 \\ m_3 l_2 + m_2 r_2 c \alpha_2 \\ m_2 r_2 s \alpha_2 \\ m_3 r_3 c \alpha_3 \\ m_3 r_3 s \alpha_3 \end{bmatrix} \quad (15)$$

4. EXPERIMENT RESULTS

In this study, hydraulic signals were compensated for through three experiences. After the motion of excavator arms worked, the dynamic parameters were obtained as shown in Table 1, using Eq. (13). To verify these parameters, the real signals were compared with the estimated joint torques after arbitrary motion and contact motion. The experiment results are shown in Figs. 7 and 8. Because of the effects of the gravity disappearance, the real hydraulic signals went down when the excavator made

contact with the environment. Therefore, reflected forces can be realized by comparing the real with the estimated joint torques.

Table. 1 Estimated dynamic parameters using gravity compensation.

Dynamic Parameters(ρ_G)	Values [kg·m]
$(m_2 + m_3)l_1 + m_1 r_1 c \alpha_1$	5733.4127
$m_1 r_1 s \alpha_1$	211.2115
$m_3 l_2 + m_2 r_2 c \alpha_2$	1437.103
$m_2 r_2 s \alpha_2$	161.5111
$m_3 r_3 c \alpha_3$	458.3555
$m_3 r_3 s \alpha_3$	371.0572

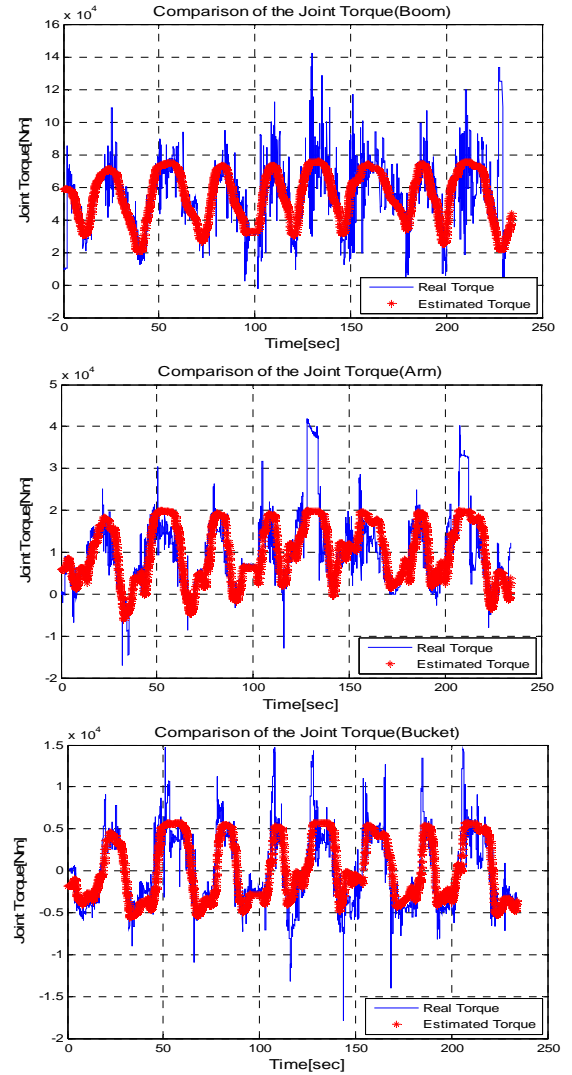


Fig. 7 Comparison of the real and estimated joint torque.

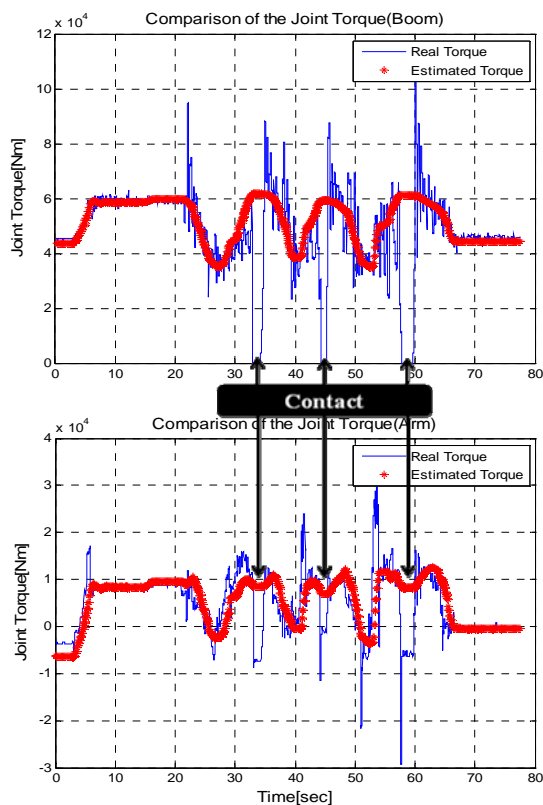


Fig. 8 Comparison of the real and estimated joint torque in the contact environment.

5. CONCLUSION

To overcome the problems with existing tele-operated excavators, a force-feedback joystick that can detect environmental information was developed, and hydraulic signals were compensated for using a regression matrix to realize the reflected forces in this study. The developed joystick and reflected forces will be applied to an excavator, and a performance evaluation will be conducted in the future.

6. ACKNOWLEDGMENT

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