

Paper:

# Control of Hydraulic Actuator Systems Using Feedback Modulator

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**Heavy-duty robots using hydraulic actuators are expected to support rescue operations by removing heavy rubble in hostile –wet, dusty, or muddy– environments. The high friction generated by their hydraulic actuator, however, makes it difficult to use them in operations requiring high precision. The servovalves used to control a hydraulic actuator precisely are more expensive than conventional proportional valves, making it impractical to install them in all joints of heavy-duty robots having many degrees of freedom. In this paper, a new hydraulic actuator control method using a feedback modulator is proposed. The proposed controller improves the performance of hydraulic systems using conventional proportional valves, making it as good as that with servovalves. This paper also proposes exclusive control for controlling multiple joints simultaneously to prevent asynchronous joint movement under unbalanced loads. The effectiveness of the proposed method is confirmed through simulations and experiments.**

**Keywords:** motion control, hydraulic actuator, feedback modulator, friction compensation, proportional valve

## 1. Introduction

In rescue operations in major disasters, it is very important to maximize task efficiency to minimize suffering. For that purpose, many rescue systems based on robotic technologies have been developed recently. One example of such rescue systems is teleoperated robots based on hydraulically driven construction machines, such as T-52 ENRYU (“supporting dragon”) developed by tmsuk Co., Ltd., for heavy-duty tasks such as debris removal [1]. Several research works on teleoperation using hydraulically driven construction machines have been conducted [2, 3]. One major difference between heavy-duty robots and conventional construction machines is that robots have more degrees of freedom (DOF) and may have more than one arm.

Most heavy-duty rescue operations involve hostile –wet, dusty, or muddy– environments where hydraulically driven actuators are appropriate. High friction at the slid-

ing part of the cylinder may, however, make it difficult to move the hydraulic cylinder smoothly, in turn making it difficult to finely adjust the end-effector position, hampering smooth rescue operations. Since friction at the cylinder may also change under a heavy load, for example, when heavy debris is raised or moved, robust control may be needed to handle such friction fluctuation.

Solution to the friction problem may involve several methods such as friction-model-based compensation, pulse width modulation (PWM) control, and adding dither signals to input [4, 5]. Some of these approaches, however, assume the use of expensive servovalves and may not so effective for systems using proportional valves having poorer response than servovalves. Owen et al. [6] attempted to reduce the effect of static friction by rotating the shaft of the hydraulic cylinder using an electric motor, but this method requires that the hydraulic cylinder itself be modified. Yao et al. [7] proposed adaptive control and Sohl et al. [8] proposed model-based control guaranteeing system stability. Such advanced control works only when commanded control input is applied precisely to the actual system and, once again, requires servovalves. Bonchis et al. [9] compared control methods applied using proportional valves from several performance aspects.

Besides friction, hydraulically driven systems have another problem when driving more than one joint simultaneously. The fact that hydraulic oil tends to flow into the cylinder under a smaller load than others makes it difficult to control multiple joints under different loads synchronously.

Heavy-duty rescue robots could potentially conduct a variety of tasks that conventional construction machines having fewer joints cannot do. T-52 ENRYU (tmsuk Co., Ltd.), for example, has two 9-DOF arms including a gripper joint. In controlling such a multijoint arm by resolved motion rate control (RMRC), i.e., commanding end-tip velocity and calculating joint velocity to realize the commanded end-tip velocity, simultaneous joint motion may occur very often. Installing individual servovalves to all joints of such robots, however, is impractical due to high cost.

In this paper, we developed a new way of accurately controlling hydraulic actuator systems with large friction using conventional proportional valves. A novel control method using feedback modulator [10] is proposed. Feed-



Fig. 1. KO-ENRYU experimental apparatus.

Table 1. Specifications of KO-ENRYU.

Length*[mm]	1500
Width*[mm]	490
Height*[mm]	540
Weight [kg]	300
Oil pressure [MPa]	10
Oil flow [l/min]	14
Payload capacity [kg]	300

\*At the resting position

back modulator, which improves control performance of systems with limited temporal and spatial resolutions, effectively cancels friction of the cylinder. This paper also proposes exclusive control for controlling multiple joints simultaneously to prevent asynchronous joint movement under unbalanced loads. The effectiveness of the proposed method is confirmed through simulations and experiments.

## 2. Experimental Apparatus

Our experimental system, KO-ENRYU, meaning “small supporting dragon,” shown in Fig. 1, duplicates the gripper and terminal wrist joint of T-52 ENRYU. The gripper part moves up and down with the wrist joint and the gripper opens and closes horizontally. Each of these two joints is driven by a hydraulic cylinder. Both cylinders are TAIYO 210C-12TA63BB140-AC-YK, 63 mm in inner diameter, 140 mm in stroke, and 21 MPa in nominal pressure, and proportional valves are NACHI ESD-G01-C520-12, 20 l/min in rated flow and 40 ms in response time. Table 1 shows the specifications of this experimental system. This system can be controlled in master-slave mode using two joysticks each corresponding to each joint. To ensure experimental replicability, control commands to the experimental system are generated by a computer in all but a few of the experiments.

We measured steady-state system outputs at varied voltage input to the proportional valve to estimate the effect of friction in the experimental system. System output became zero when input voltage was less than 1 V, indicating the effect of friction. Although maximum voltage input to the proportional valve is 5 V, output saturated for inputs exceeding 2.5 V. In the preliminary experiment, we

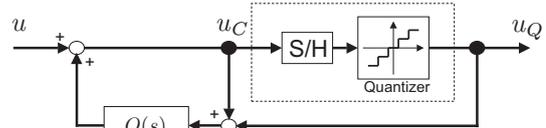


Fig. 2. Feedback modulator (FM).

roughly estimated the relationship between proportional valve input voltage and resultant oil flow, excluding the friction effect, at 10 l/(minV). Details of the experimental system identification are described in Appendix A.

## 3. Feedback Modulator

Ishikawa et al. [10] proposed a feedback modulator, which is used as the base of hydraulic actuator control we are proposing.

Feedback modulator is a plug-in compensator which makes an actuator with limited temporal and/or spatial resolutions behave approximately as an actuator producing continuous output. This is also applicable to actuators with slow output updating, with a limited set of discretized output such as even {1, 0, -1}, and with uneven time and/or quantization intervals.

Figure 2 illustrates the configuration of feedback modulator. An important feature of the feedback modulator is that error due to the sample and hold (S/H) and quantization, denoted by  $\eta = u_C - u_Q$ , is fed back to original input  $u$  via filter block  $Q(s)$ . Original input  $u$  and quantized input  $u_Q$  are related as follows using  $Q(s)$ :

$$u_Q = u + \{1 - Q(s)\}\eta. \quad \dots \dots \dots (1)$$

That is, original signal  $u$  is transferred to  $u_Q$  as is, while error  $\eta$  is shaped by  $1 - Q(s)$  in the frequency domain.

If  $Q(s)$  is chosen so that

$$1 - Q(s) = \left( \frac{\tau s}{\tau s + 1} \right)^2, \quad \dots \dots \dots (2)$$

$\eta$  is shaped by a low-pass filter, meaning that the feedback modulator can cut off quantization error in the low frequency range.

If actuator output updating is fast enough, the system is regarded as a continuous time system without S/H block. In such an ideal case, any small  $\tau$  can be set so that most frequency components of  $\eta$  are filtered out. In practice, however, actuator output updating is finite. Letting the updating period be  $T$ ,  $\tau > T$  must be satisfied to ensure system stability.

Parameter  $\tau$  in Eq. (2) should be as small as possible while satisfying  $\tau > T$  so that quantization error cutoff region is as wide as possible. We chose  $\tau = 1.05T$ . The pulse transfer function of  $Q(s)$  is then given by

$$Q(z) = \frac{0.9816z^{-1} - 0.6044z^{-2}}{1 - 0.7716z^{-1} + 0.1489z^{-2}} \quad \dots \dots (3)$$

with  $z$  transformation.

To demonstrate the effectiveness of feedback modula-