Development of A Hydraulic Bilateral Servo Actuator for A Patient Supporting Robot

Y. SAITO, K. OHNISHI, Y. SUNAGAWA, S. TAGUCHI

*Dept. of Industrial and Mechanical Engineering, Faculty of Science and Engineering, Tokyo Denki University
Ishizaka, Hatoyama, Hiki, Saitama, Japan, 350-0394
Tel.: +81-0492-96-2911, Fax.: +81-0492-96-6544
(E-mail: saito@n.dendai.ac.jp)

**Nihon Shinkan Co., Ltd.
Nishigo,Nishi-shirakawa,Fukushima,Japan, 961-8061
Tel: +81-248-25-2141,Fax:+81-248-25-0593

ABSTRACT

One major difficulty in nursing the bedridden is moving their body. This includes lifting and carrying them from one place to another, as well as changing their body posture. Because they are lifting a heavy solid weight while in an unstable posture, the caregiver usually suffers back pain due to this work. We propose a solution by replacing this labor with robotics technology to lift and/or carry a person. The robot is designed with the smooth, high torque hydraulic actuation, and the bilateral servo system for the control to meet the necessity of the service. The superiority of this robotic device is in its interface and output torque. The bilateral servo system allows the robot to be directly operated (holding the end of the arm) and to control an average weight of a Japanese adult (e.g. 60 kgf) with little effort (e.g. 1 kgf).

KEY WORDS

robot, patient supporting ,prototype, hydraulic actuator , bilateral servo

INTRODUCTION

This paper describes an actuator control system with applications to assist caregivers in difficult work, such as lifting and carrying their patients to change diapers and bath.

Changing diapers is usually performed by two caregivers in an unstable posture at the bedside, one lifting the patient's middle and lower body and the other cleaning the body and replacing the diapers. Moving the bedridden person into a Japanese home bathing facility, into a deep bath tub, is done by multiple people.

Caregivers must lift and carry a person out of the bed and then safely take him/her into a small room with a wet floor. Thus, at-home nursing services providing bathing services are in high demand in Japan. This is often accomplished by using an easily assembled bathing equipment with flexible tub at the bedside, Fig 1, thus minimizing the trouble of carrying a person. However, still multiple workers needs to perform for this task and a space for the equipment and the work.

Statistics in Japan indicate that the bedridden are under supervised care, on an average, approximately 8.3 months until passing away. Caregivers are required to
provide certain services, e.g. changing diapers and bathing, which results in moving a heavy weight approximately 2000 times during these months. This kind of heavy physical labor is a major cause of suffering backache and other disorders of the body, including mental stress. The problem is the rapidly increasing population of the elderly in Japan, requiring families to take care of their bedridden relatives at home. Therefore, methodologies are desperately being sought to overcome these issues before they become critical. Robotic technologies are definitely the support which the Engineer can provide for this need.

Assisting robot systems that have been designed for the same purpose, capable of transferring an average weight of the Japanese adult, in previous work are MELCONG and Patient supporting robot of Tokai University. MELCONG has been developed by Nakano et al. at MITI, Japan. It is hydraulically powered and equipped on a multi-directional vehicle, but has a deficit due to its large size. Patient supporting robot is a teleoperated transportation robot, developed by Tokai University, Japan. It is electrically motor driven, however it has drawbacks of the large size and the overall impression resembling two arms of an industrial forklift for lifting a person.

In this research, hydraulic actuation is implemented due to its high output torque and smoothly connected movements. As for controllability, the bilateral servo system is composed clearing the problem in interface, enabling the caregiver to operate the robot arm by guiding it directly with their hand and without the need of preprogramming or keyboard input as seen in industrial robots. This hydraulic system consists of a light weight compact actuator, two simple cylinders in a master-slave relationship without requiring an external hydraulic power source. The bilateral servo system has been formally utilized for the manipulator’s servo system applied to robots for nuclear power plants and medical laboratories handling high radioactive material in Fuji’s work.2) The position controlling symmetric bilateral servo and force controlling force feedback bilateral servo are composed to satisfy the requirements of the application. The principle of the actuation mechanism and its application to the robot, and the experimental results of the bilateral servo system are discussed.

Indispensable Technology for Care-Service Assisting Robot

The requirements on care service assisting robots are broadly categorized in two sections: 1) support to maintain the body’s daily function and 2) support for movement of the body’s weight. The former cases the key routines in daily life, e.g. feeding and cleaning, for keeping the subject in a healthy condition.

The latter helps by directly holding the heavy body weight during movements and transportation, e.g. changing diapers, carrying the patient, and placing in and out of a tub. The former can be performed with a robot arm mounted on an externally powered wheelchair, which is operated by the handicapped individual. The latter also involves a robot operated by the caregiver, and this is our eventual research target. The latter also includes indirect feedback control and requires a simple and efficient operating interface. Factors such as residual vibration that can injure the subject must be thoroughly considered for the robots which are directly in contact with a human body.

Interacting with humans requires a higher level of safety, and is the key issue in all assistance-oriented robot systems. The requirements of safety in the diaper exchanging robot are:

1. To maintain the current condition and complete the target task by switching to the reserve power supply when the main power goes down.
2. To complete the target task with the subject maintained in a safe condition, even when the cable is disconnected. It may be slow and less accurate, but it must finish all the required actions in the specified task.
3. To pause temporarily by immediately shutting down the power when the system becomes seriously uncooperative, and easy to reboot the system when the problem is solved.
4. To have protective cover around the robot body for preventing the robot from harming humans in the event of unexpected contact.
5. To possess a function and structure to prevent damage to and from its working environment.
Table 1 The required specifications of the robots

<table>
<thead>
<tr>
<th></th>
<th>Ex-powered Wheelchair mounted assisting robot</th>
<th>Body holding robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.O.F.</td>
<td>5 - 6</td>
<td>3 - 4</td>
</tr>
<tr>
<td>Necessary power</td>
<td>0.5 kgf</td>
<td>60 kgf</td>
</tr>
<tr>
<td>Action speed</td>
<td>1 Hz</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Operator</td>
<td>The handicapped</td>
<td>The caregiver</td>
</tr>
<tr>
<td>Body part used for Operation</td>
<td>most easily movable part of body</td>
<td>Hand and arm</td>
</tr>
<tr>
<td>Robot Interface and command</td>
<td>Joystick / angle and button switch</td>
<td>Arm end / position, orientation and force</td>
</tr>
<tr>
<td>Control method</td>
<td>Position control</td>
<td>Position and Force control</td>
</tr>
</tbody>
</table>

The safety-based control of the robot operating software and hardware is under experimentation with the assisting robot in the laboratory. The required specifications of the robots are shown in Table 1.

The most difficult requirement in this table is to obtain an actuator with the capability of holding a human body’s weight. Hydraulic is selected as a power source for its smoothness, high torque output, and light weight. The geared motor is not of choice in this type of robot, because of the necessary motor size being larger for the output requirements, instability at continuous loads of 60 kgf, and difficulties in compact design.

Figure 1 shows the schematic of our body holding robot in progress. This robot is designed to automate the labor of diaper exchange. It is implemented on the bedside to remove and replace the diaper and clean the body.

Bilateral Servo’s Force Transmission Mechanism

Figure 2 shows the basic structure of a force transmission mechanism in the bilateral servo system. It consists of two cylinders, master and slave, with the master piston coupled to servo motor through a linear movement mechanism. Each of the two passages on the cylinder are connected in parallel to the other cylinder through flexible tubes with embedded pressure sensors, such that the pressures on the piston and bottom are measured. The displacement of the piston stroke is measured with a potentiometer. If the displacement of the piston between the slave and master cylinders are sent to the servo motor as feedback, the system performs a symmetric bilateral servo. If the difference between the ideal and present inner cylinder pressure is given in the feedback, the system performs a force feedback bilateral system.3,4

\[
F_1 = \frac{2\pi \cdot n \cdot \eta \cdot T}{\nu},
\]

\[
F_2 = \frac{A_2}{A_1} \cdot \frac{2\pi \cdot n \cdot \eta \cdot T}{\nu},
\]

(Eq. 1)

\(v\) is the piston velocity, \(\eta\) is the transformation ratio, \(T\)

A1: internal cross section of master cylinder
A2: internal cross section of slave cylinder
P1: pressure back
P2: pressure front
F1: force from a master cylinder
F2: force from a slave cylinder
X: master stroke
Y: slave stroke
is the motor output torque, and \( n \) is the rotational velocity.

If the flow quantity of the master cylinder’s output and the slave’s input are assumed to be equal for the two cylinders connected with tubes,

\[
A_1 \cdot \Delta x = A_2 \cdot \Delta y \tag{Eq. 2}
\]
is to be defined, where \( \Delta x \) is the master piston position difference and \( \Delta y \) is the slave’s. Thus, the position difference on the slave piston is:

\[
\Delta y = \frac{A_1}{A_2} \cdot \Delta x = \frac{F_1}{F_2} \cdot \Delta x \tag{Eq. 3}
\]
and the output torque will be influenced by the ratio \( A_1/A_2 \). That is, the torque on the slave piston increases when \( A_1 < A_2 \), and the velocity increases when \( A_1 > A_2 \). The output on the slave piston’s dependency on the servo motor output torque is derived from this equation.

**Figure 3** shows the force transmission mechanism of the bilateral servo system.

![Fig 3 The force transmission mechanism of the bilateral servo system](image)

The dotted line shows the symmetric bilateral servo system; the solid line the force feedback bilateral servo system. The piston movements, in both master and slave, are followed by reading the position on the linear potentiometer. If the target movement \( \Delta L \) is known, the tracking servo is applied as,

\[
\Delta L + \Delta y = \Delta \xi_{II} \tag{Eq. 4}
\]
where \( \Delta \xi_{II} \) is an error signal.

The semiconductor pressure sensor is mounted inside the cylinder to measure the inner pressure. The piston side and the bottom side pressure, \( P_1 \) and \( P_2 \), are usually equivalent: \( P_1 = P_2 \) when the piston is still. When the pistons are loaded, the force on the slave piston is driven as Eq. 5 from Eq. 1 and 2, where \( p/f \) is a function of pressure at pressure equivalent condition.

\[
F_z(p_f) = \frac{A_2}{A_1} \cdot F_1(p_f) \tag{Eq. 5}
\]

The pressure equivalent condition in Eq. 5 is appropriate even when the slave piston is loaded with the body weight, approximately 60 kgf. When a small load is added to the slave side, the equation will be:

\[
F_z(p_f) + \Delta F(p_f) = \frac{A_2}{A_1} \cdot (F_1(p_f) + \Delta F(p_f)) \tag{Eq. 6}
\]

The master side cylinder is required to balance the pressure, and the servo controls the motor to decrease the pressure difference. The actuator is controlled with this system in Fig. 3 and therefore is easy to directly guide the end of the arm with a small force, even if it is already loaded with a heavy weight.

The superiority of this system arises when it is controlled in an open loop.

**Figure 4** shows the repeatability characteristics of the system when 40 kgf of load is constantly given to the slave piston. The steady movement of the slave piston observed shows that it is controlled synchronously to the master without overshooting or vibrating, even when the system is not getting a feedback signal and the servo motor on the master cylinder is manually driven. This is an important factor that allows the system to be said to have a safe and tolerant operation with a wide range of stability.
The safety system required for supporting robot of a patient is incorrect action by cutting of feedback signal or a signal failure in the most case. In other words, the follow-up between master and slave in open loop influences on the safety.

**Specification of the Position Control in Bilateral Servo System.**

Table 2 shows the size of the prototype hydraulic cylinder developed for the care assisting robot. Normally, off shelf cylinders are classified into pneumatic and hydraulic. The hydraulic cylinders have large steady pressure capacities, e.g. 3MPa, and are heavy, while the pneumatic cylinder lacks the capability to be used as an hydraulic. Therefore a special cylinder with a pressure sensor installed has been developed for the robot's actuator. The master side of this actuator is an integration of a cylinder, a linear movement mechanism, and a geared motor coupled together. A ceramic potentiometer is installed inside the cover to measure the piston's position. Figure 5 shows the relationship between time and position of repeated position control on a symmetric bilateral servo with a constant 40 kgf load on the slave cylinder. The input signal is a sign curve and, as seen, the repeatability to it is high as 0.06 % where the full scale is 20 mm.

![Fig 5 The relationship between time and position of repeated position control](image)

**Table 2 The size of the prototype hydraulic cylinder**

<table>
<thead>
<tr>
<th>Master · Slave cylinder internal diameter × Stroke</th>
<th>Pressure sensor</th>
<th>Position sensor</th>
<th>Motor</th>
<th>Power (Slave)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 × 80</td>
<td>20 × 150</td>
<td>Stroke 200mm</td>
<td>16 watt motor, speed-reduction gears1/25</td>
<td>460N</td>
</tr>
<tr>
<td>30 × 80</td>
<td>30 × 150</td>
<td>Stroke 300mm</td>
<td>16 watt motor, speed-reduction gears1/25</td>
<td>1040N</td>
</tr>
<tr>
<td>50 × 150</td>
<td>50 × 250</td>
<td></td>
<td>16 watt motor, speed-reduction gears1/25</td>
<td>2890N</td>
</tr>
</tbody>
</table>

**The frequency characteristic**

Figure 6 shows the frequency characteristic of the actuator used in Table 2. The figure shows the responses of no-load, 20 kgf, and 40 kgf of load. As seen in the figure, the frequency response with no-load is the least desired. The reason being on the system composing a servo system is based on pressure equivalence, therefore if pressure difference ratio is small, the frequency response is low. The gravity causing the weight of the robot is introduced to improve the response in actual use. The response is better when the load approaches the maximum capacity, and the experimental data shows a response of approximately 1.8 Hz, -3 dB at load of 40 kgf.

The movement principle in Fig.3 is decided by connecting a cylinder with other one through flexible tubes with a pressure balance of the antagonism. And the condition of a pressure balance changes according to the load.

![Fig 6 The frequency response](image)
Specification of the Force Control in Bilateral Servo System.

**Fig 7** The output response of the slave piston with the 60 kgf previously loaded.

**Fig 8** Specification of the Force Control

**Figure 7** shows the output response of the slave piston with the 60 kgf previously loaded. The force feedback bilateral servo is implemented and $\Delta F(p/pf) = e \sin \psi t$ entered from the master side. The $\Delta F(p/pf)$ is manually provided to the slave piston in actual use. **Figure 8** presents a proper vibrating condition at the target pressure 0.367 MPa, when holding the load: 40 kgf. The threshold value is set within 10% of target pressure. As seen in the figure, the hold time of the vibration erupts exponentially, and the system falls in to a holding condition when the cycle exceeds 30 seconds.

**Conclusion**

An actuator with power sustaining 60 kgf with friendly interface, relieving caregivers from special learning and training for robot operation, has been developed. Its appropriateness for use in human coexisting environments has been presented. The structure providing compact, safe, and high torque force transmission mechanism for the care assisting robot has been described. It has prove the superiority of composing bilateral servo system, through experimental data, extends the stable range of position and force control, and enables the characteristic to be as high as 1.8 Hz. As an application of this actuator, the diaper changing robot, bathing assisting robot, and externally powered lifter should be further developed.

**REFERENCES**

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