EXOSKELETON ROBOT USING HYDRAULIC BILATERAL SERVO ACTUATOR SYSTEM FOR NON-AMBULATORY PERSON’S TRANSFER

Julien MONNET (TDU/ENSMM), Yukio SAITO (TDU), Kengo ONISHI (TDU)
Tokyo Denki University – Ecole Nationale Supérieure de Mécanique et des Microtechniques
Ishizaka, Hatoyama-cho, Hiki-gun, Saitama 350-0394, Japan
julien.monnet@ens2m.org

ABSTRACT
This paper reports on an exo skeleton robot that offers a unique design and high capabilities to transfer non-ambulatory people among bed, futon, chair or toilet, reducing the burden of caregivers. This “master-slave system” power assists the caregivers when transferring the non-ambulatory person’s body weight. This device moves with an exclusive Hydraulic Bilateral Servo Actuator (HBSA) system and it is controlled by a pressure control system using Digital Differential Analyzer (DDA) method for sending pulse to the motors. This combination provides smooth and stable movements during transportation.

The contributions of this paper are threefold: (1) Explanation of a unique design of an intelligent transfer device (2) Description of the HBSA system with tests and results (3) Development of a pressure control system using DDA method. We expect to create a useful health care device which will improve the work and the health of caregivers and will reduce the accidents of fall and injury during transportation.

KEY WORDS
Intelligent instrumentation, Robotics, Rehabilitation Engineering, Power assist device.

1. Introduction

Non-ambulatory persons, such as aged people or severely injured, often need help from caregivers or nurses in everyday life to transfer or change posture on a bed, toilet, bathtubs or a wheelchair. There are two main problems of providing transfer assistance. First, concerning the health of caregivers, lifting and moving human body weight repeatedly is excessive burden for them. A recent survey shows that a third of nurses experience injury when moving non-ambulatory patients [1]. Furthermore, the insecurity leads to safety problems of the persons being transferred. According to current statistics, a half of non-ambulatory persons experience fall and injury when being transferred from a bed to a wheelchair [2].

Moreover, the rate of aged people is increasing in industrialized countries. In 2025, around 30% of the European population will be over 65 years-of-age [3]. It can be expected that in the near future, a transportation system which augments the power of caregivers will be very useful. A survey conducted by the National Institute of Standards and Technology (NIST) showed that there is a real need for devices that provide lift and transfer of the disabled [4].

The aim of this research is to develop an intelligent assistive device which fulfills the two following points:
- Capable of lifting a person from bed top (high point) or floor-matted futon (low point) to a wheelchair, vice versa (Figure 1).
- Capable of reducing the force needed by the caregiver to lift and hold the person to a safe and acceptable level.

To achieve this goal, a prototype robot and a control system is developed. The controller was built to control the pulses and the pressure necessary to lift a person from a bed to a wheelchair.

The organization of this paper is as follow: The exclusive design of this exoskeleton system using HBSA system is detailed in Section 2. The control system using both open-loop program and an algorithm using DDA method to lift the human body weight is explained in Section 3 and snapshots of the robot are shown in Section 4.

Figure 1. Non-ambulatory persons transferred from bed to wheelchair

2. Development of the hardware

2.1. The Exoskeleton system

The proposed system is a master-slave control type. The slave unit is an exoskeleton in which is connected to the caregiver at the forearm. The caregiver is capable of easily manipulating the slave system and holding a person in
his/her arms (Figure 2 and 3). This exoskeleton system fulfills the following specifications:

- High-power output: capable of lifting up to 600 N.
- Multiple degrees-of-freedom: seven degrees-of-freedom mechanism designed to reproduce the caregiver’s motions without limiting the movable range of the joints.
- User-friendly interface: direct operation input to the slave unit. No special training required for control.
- Real time control: smooth and stable movements throughout the transferring support.

This system is designed to easily lift a person in the range of a height of 200 mm from the ground (e.g., a futon) up to approximately 800 mm (e.g., a high bed). The mechanical hardware of the exoskeleton is composed of left-right symmetrical parts, but the control system is developed for independent control of each part (Figure 4). Figure 5 shows the kinematic model of the robot and the name of the different parts.

Experiments using motion capture system are conducted to confirm the restriction to the movable range of the user donning the system and performing transfer support motions. Data are plotted for certain position and posture during the task in Figure 6. The shoulder flexion angle variation is shown in Figure 7. The data represents the transferring movement from a 400mm-height wheelchair to a 700mm-height bed. The blue plot shows the angle with the assist of the slave unit, the red plot without the system. The two curves are relatively similar showing that the slave system is not a nuisance to the caregiver. Furthermore, the specifications of the six articulations of the exoskeleton system (on one side) with movements, angles, and output power are described in Table 1.
2.2 The Master Unit

A geared motor, activated by a motor driver unit (Servopack, Yaskawa, Japan), is coupled to a ball/screw which transmits the motor shaft rotation to the linear motion of a master cylinder piston. See Figure 8. Altogether, twelve AC motors are linked to the twelve cylinders on the master unit, as shown in Figure 9. The dimensions of the master unit rack, including the master cylinders and the Servopacks are 27 mm wide, 54 mm long, and 1370 mm high.

<table>
<thead>
<tr>
<th>Part</th>
<th>Mobile part</th>
<th>Actuator</th>
<th>Stroke</th>
<th>output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-1</td>
<td>Legs</td>
<td>Flexion</td>
<td>30 [deg]</td>
<td>5105 [N]</td>
</tr>
<tr>
<td>Li-2</td>
<td>Up/Down</td>
<td>Mono-articular</td>
<td>200 [mm]</td>
<td>1838 [N]</td>
</tr>
<tr>
<td>Li-3</td>
<td>Back</td>
<td>Flexion</td>
<td>40 [deg]</td>
<td>5105 [N]</td>
</tr>
<tr>
<td>Li-4</td>
<td>Right/Left</td>
<td>Mono-articular</td>
<td></td>
<td>2553 [N]</td>
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<tr>
<td>Li-5</td>
<td>Shoulder</td>
<td>Flexion</td>
<td>43 [deg]</td>
<td>1838 [N]</td>
</tr>
<tr>
<td>Ro-6</td>
<td>Wrist</td>
<td>Rotating</td>
<td>60 [deg]</td>
<td>9 [N·m]</td>
</tr>
</tbody>
</table>

2.3 HBSA system

Hydraulic Bilateral Servo Actuator (HBSA) system consists of a motor, a motor driver unit, a master cylinder and a slave cylinder, with the potentiometer on the pistons and pressure sensors mounted in the tubing pipes connecting the master and slave cylinder. See Figure 10. Eventually, the 12 slave cylinder on the exoskeleton system connected to the 12 master cylinder and motor on the master unit rack composes 12 independent HBSA systems. The tube pipes linking the master and slave cylinders are filled by high grade machine oil, viscosity approximately 56 [cSt]. Figure 11 shows the entire master-slave power assist system.

Three types of HBSA slave cylinder: bi-articular, mono-articular, and rotary, were developed in the previous research and development projects for powered upper and lower limb orthoses. All three types of modified cylinders are used in the exoskeleton slave unit. The pictures of the bi-articular, mono-articular, and rotary cylinders are shown in Figures 12 and 13.

The advantage of the HBSA structure is that it allows a light-weight arm design with high output by separating the master and slave units. Furthermore, when compared with a directly motor-driven system, the HBSA structure enables easy haptic feedback to the user based on pressure and smooth movements by the oil viscosity and compressibility.

There are two types of sensor in the HBSA system: position and pressure. Pressure sensors are attached to cylinders and pressure in all the system’s chamber is measured. Both position and pressure sensors are attached to the slave unit for two main reasons. First, it is because the HBSA system could induce some precision errors. Then, the most important variations are observed in the slave system which supports the patient load and the operation movement of the caregiver. The pressure
sensor’s measurable maximum pressure inside the tubes is approximately 2 [MPa].

### 3. Control system

#### 3.1 Organization of the control system

This system is composed by twelve motors (six on each side). The aim of the control system development is to sequentially control these twelve motors along the desired trajectory with precision. The best configuration for trajectory control is to drive all the motors with a pressure feedback control. However, the microprocessor used for our controller has only four A/D converter ports, so only two pairs of HBSA with position/feedback pressure control is possible. To resolve this problem, it has been decided to control ten motors by an open-loop program and two by a pressure control program using Digital Differential Analyzer (DDA). The pressure control being more accurate, the two motors situated at the back side (cf. previous figure 5) which support the maximum load (the highest pressure), will be controlled by pressure control system.

In this section, first the open-loop program, tests and results using HBSA system will be described. Then, the pressure control using DDA will be discussed.

#### 3.2 Open-loop control system

The proposed open-loop control program has the possibility to control the direction and ON/OFF timings of ten motors rotation, independently and sequentially. After creating the open-loop program, experiments were conducted to verify the motor operation and to justify the necessity of motor control by pressure control feedback program. Pressure sensor and potentiometer feedback were measured while increasing loads were applied to the robot’s arms.

The following diagrams (Figures 15 to 17) show the pressure sensors and potentiometers feedback of the elbow joint actuator (cf. previous figure 5) while loads on the arm were increased. The bi-articular HBSA cylinder is mounted as an elbow actuator and three pressure sensors: upper, middle and lower pressure sensors (Figure 14) are installed in the bi-articular HBSA. These diagrams show that with no load, the angle and the inner pressure are stable and can be controlled easily. However, applying and adding the load on the robot arm, the inner pressure and the elbow joint angle cannot be controlled with satisfying accuracy. In the last case, a pressure control system is obviously required for accurate elbow joint angle control.
3.3 Aim of the pressure control system

The frequency of pulses and the speed of motors are controlled using pressure sensor’s information. This servo-control system is composed of seven steps which are repeated throughout the performance:

a) First, the caregiver performs the task with the slave unit to adjust the parameters (trigger to start the program).

b) The cylinder inner pressure changes.

c) Pressure variation is detected by the sensors.

d) The software calculates the force needed to assist the caregiver and to move freely.

e) Motor driving pulse commands are sent to the ServoPacks.

f) Finally, the master unit motors rotate to reach the target pressure (previously calculated).

g) Motor rotates to meet the calculated force for assisting the caregiver to lift the patient and the measured pressure match.

Figure 18 shows the structure of the feedback control system for lifting a patient.

3.4 Environment of the pressure control system

The micro-controller receives the feedback signals from pressure sensors. It also links the servo-packs and the computer together (Figure 19 and 20).
The main idea of the pressure control system is to control the inner pressure of each cylinder to control the trajectory of the robot. Then, changing the rod and the bottom pressures (differential pressure) inside the cylinder, it is possible to compute and control the target force for lifting the client (Figure 21). The output force for lifting the client is defined by the following equation:

\[ F = P_1 \times A_1 - P_2 \times A_2 \]  

(1)

with \( P_1, A_1, P_2 \) and \( A_2 \) explained in Figure 21.

Three cases are possible (Figure 21):
- If \( F=0 \) the piston stay at the initial position.
- If \( F>0 \) the piston in the bottom side of the cylinder becomes more important than the pressure in the rod side.
- If \( F<0 \) the inner pressure of the bottom side is smaller than the inner pressure of the rod side.

![Figure 21. Principle of the pressure control system](image)

![Figure 22. Kinematics equations (link α and F)](image)

Depending on desired angle and trajectory of the robot, it becomes possible to calculate the desired inner pressure. The proposed program runs on following steps. First, the values are entered calculate the target inner pressure. Then, this target inner pressure is compared to the value measured by pressure sensors (measured pressure). Finally, pulses are sent to the motors until the desired target pressures \( P_1/P_2 \) inside the cylinder are reached and are the same than measured pressures \( P_1'/P_2' \) (Figures 23).

![Figure 23. Flowchart of the pressure control system](image)

### 3.6 Pulses control system with DDA

In this system, a pressure control algorithm is used to...
calculate the necessary force to lift someone and to get the feedback of pressure sensors while a control system by DDA (Digital Differential Analyzer) is used to control independently the frequency of pulses sent to each motors. It becomes possible to control the speed of motors with a high or low frequency depending if there is more or less pressure inside the slave cylinders. In this case, both pressure and DDA algorithm are used to get an entire close-loop control system to drive velocity command servomotor. This control method has the advantages to be simple, cheap and with a high precision for controlling independently the speed of all the motors depending on the pressure feedback from sensors. However, the main inconvenience is the possibility to control only two motors at the same time using one micro-controller with 4 A/D ports. The particularity of making operations with a DDA is due to its “Incremental Computer (IC)”. It is a computer which stores variables as the difference between their actual value and an absolute initial value. It can solve a variety of differential equations with high accurate results. Sinusoidal waves have been created based on the theory of the IC system of the DDA. It gives the possibility to change freely the number of bits (clock pulse), the frequency and the amplitude of the sinus waves (Figure 24 and 25). Each cycle of the sinus wave has been divided into fourth quadrants, only the direction of the tangent vector changes (Figure 26).

Finally, using the previous control method of sinusoidal waves, it becomes possible to send pulses controlling the rotation speed of each motor independently.

3.7 Pressure control system with pulses controlled by DDA

The following flowchart (Figure 27) shows the structure of the final program. It details the combination of the DDA program to control pulses and pressure control program to calculate the necessary force inside the cylinders to lift the client.

4. Snapshots

Experiments were conducted to test and check the complementary between the open-loop and the pressure control system without a subject (Figure 28). The targeted trajectory tracking is performable with satisfying accuracy, and both programs are working well together.
5. Conclusion and future work

This exoskeleton is a user-friendly intelligent system that reduces the burden for caregivers. It uses an exclusive HBHA master/slave system with easy-feedback and a light-weight arm to produce high output and smooth movements.

The assembled robot includes the pressure sensors and the control environment of the motors. Besides, the open-loop program, the control algorithm for computing the frequency of the pulses by DDA and the pressure control program are implemented and performable.

The programs have to be tested and ameliorated using the exoskeleton system’s output. Moreover, experiments between the hardware part and the control system have to be developed. Especially, the relationship between the feedback of pressure sensors and the frequency of pulses sent to the motors with DDA pressure control system have to be analyzed. Moreover, to develop a robot with a full pressure control system, it would simply require installing a micro-computer with 24 A/D ports.

To conclude, this exoskeleton robot assists the caregivers to lift the disabled client from a bed or from a futon. A good communication and compatibility between the mechanical part and the software has been developed to get smooth and safe’s movements. In the future, this type of robotic system will be more likely to be used especially in areas and countries which are rapidly graying, and will enhance both caregiver’s and disabled person’s health and safety.

References