Proceedings of 2013 ICME
International Conference on Complex Medical Engineering
May 25 - 28, Beijing, China

Development of a Human Upper Limb-like Robot for Master-slave Rehabilitation

Shuxiang Guo[*1,*3] Songyuan Zhang[*2] Zhibin Song[*1] and Muye Pang[*2]

[*1]*Department of Intelligent Mechanical Systems Engineering*
[*2] *Graduate School of Engineering*
Kagawa University
Hayashi-cho, Takamatsu, 761-0396, Japan
{s12d505,s11g528}@stmail.eng.kagawa-u.ac.jp

[*3]*College of Automation, Harbin Engineering University*
145 Nantong Street, Harbin, Heilongjiang, China
{guo, song}@eng.kagawa-u.ac.jp

Abstract – **Master-slave rehabilitation systems are superior to traditional robotic rehabilitation systems on the respect of enhancing therapists' abundant experience. In this paper, a human upper limb-like robot which can mimic the spasticity of stroke patient is proposed as the master device. Therapists can operate this device to perform rehabilitation. In order to mimic the severe spasticity of patients, the device is required to exert high torque. Therefore, high reduction gear was mounted on a stepping motor. As a result, the device becomes non-backdrivable, which decreases its operability. Many researches have ever proposed the admittance control, Series Elastic Actuator (SEA) to solve this problem. Considering about the conditions of our device, admittance control can be realized with a high-accuracy load cell. However, a load cell induces instabilities and high cost. Similar with the SEA, a new structure is proposed in this paper. Two elastic bars are applied to connect the robot's forearm and upper arm. By detecting the bending of these bars, the interaction force exerted on this robot can be calculated. The tiny bending is enlarged with a long bar so that the deformation of elastic bars can be more accurately detected with an optical mouse. To evaluate the efficacy of proposed structure, experiments were conducted to exert three levels resistance using the device. Experimental results show that the proposed structure is effective, and the exerted resistance can be adjusted with it.**

Index Terms – Master-slave rehabilitation, Non-backdrivable, Series Elastic Actuator (SEA), Optical mouse.

I. Introduction

According to statistics, approximately 795,000 people suffer from a new or recurrent stroke every year [1]. Moreover, intensive movement training of the motor tasks is required to induce long-term brain plasticity based on experimental evidence [2]. In recent years, robot-assisted rehabilitation appeared to help patients to recover motor function, providing repetitive movement exercise. One of the earliest typical robots for upper limb rehabilitation is MIT-MANUS. It can guide or perturb the patient's upper limb movement under pre-defined task-oriented task [3]. GENTLE/s was a machine mediated therapy for neuro-rehabilitation. GENTLE/s used haptic and virtual reality (VR) technologies to deliver therapy [4]. The ARMin robot can support entire arm for rehabilitation. A patient-cooperative control strategy was developed to assist patient during activities of daily living (ADL) training tasks [5]. Guo and song developed a novel rehabilitation training and assessment system for upper extremity [6]. Guo and song developed a novel kind of exoskeleton device which can perform both active training and passive training for home-rehabilitation [7].

Those systems can provide the exercises for patients that assist them in daily life activities. However, the trajectories that the patient's arm must follow are programmed before the training [8]. On the other hand, patients need the supervision of the therapists as well as their active guidance and their expertise. Master-slave rehabilitation system is superior to traditional robotic rehabilitation system on the respect of enhancing therapists' abundant experience. Some research groups have be dedicated to the master-slave rehabilitation system [9].

In this paper, a human upper limb-like robot which can mimic the spasticity of stroke patient is proposed as the master device. In order to mimic the severe spasticity of patients, the device is required to exert high torque. As we know, for the traditional robot arm, the connection between an actuator and its load is commonly designed to be as rigid as possible. However, it will result in large and heavy units to obtain a low speed and high torque. Therefore, high reduction gear was mounted on a stepping motor. However, the reduction gear has several drawbacks such as increasing the reflected inertia at the output of the gearbox and friction, therefore the device is intrinsically non-backdrivable, which decreases its operability. For these reasons, the impedance control which requires the backdriviablity and light inertia becomes impossible. Admittance control can minimize the friction and the effects of inertia by controller, measuring the force by a load cell. However, a load cell induces instabilities and high cost. To overcome these disadvantages, the Series Elastic Actuator was designed by adding an elastic element between the motor and its output [10]. Guo and song proposed a method which provides a wide approach for human machine interface (HMI) in which the device is non-backdrivable, and it is difficult to obtain the contact force information directly. In this method, the motion of human body is measured with MTx sensor other than the motion of device, and it is also a kind of SEA intrinsically [11], [12].

This paper is organized as follows. In section I, some background and relative researches are introduced first. In section II, the design of the human upper limb-like robot will be introduced. In section III, some experiments are conducted

978-1-4673-2969-9/13/$31.00 ©2013 IEEE

to exert three levels resistance using the device. The last section presents the conclusion and future works.

II. Design of the Human Upper Limb-like Robot

In order to improve the operability for the therapist, the dimension and the range of movement were designed based on real human's arm. The length of the linkage bars was set at 80mm, in order to define the bending deformation within a measurable range. Some parameters of the robot are showed in TABLE I. A structure design sketch was designed with the CATIA V5 for processing the component of the robot (Fig. 1).

TABLE I
DIMENSION OF THE MAIN PARTS

	Length(mm)	Diameter(mm)	Material
Forearm	200	65(outer)	Plastic
Upper limb	170	76(outer)	Plastic
Linkage bar	80	5	Steel
Long bar	270	4	Steel

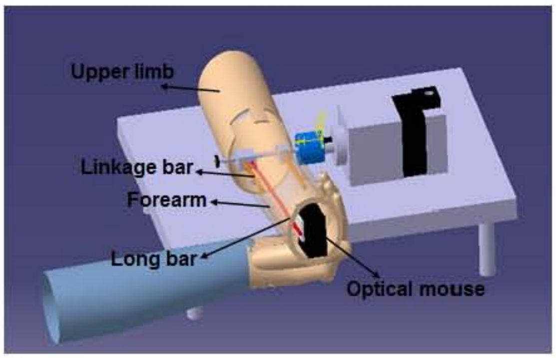


Fig. 1 The whole structure design sketch with CATIA V5

The device is required to exert high torque for mimicking the severe spasticity of patients. Therefore, high reduction gear was mounted on a stepping motor. Some parameters of the steeping motor are showed in TABLE II.

TABLE II
PARAMETER OF STEEPING MOTOR

	Maximum torque (N*m)	Maximum speed (rad/min)	Reduction ratio
Steeping motor	16	1.25	120

As a result, the device becomes non-backdrivable caused by the high reduction ratio (1:120), which decreases its operability. To solve this problem, the convenient SEA was designed by adding an elastic element between the motor and its output. Similar with the convenient SEA, two elastic bars were applied to connect the robot's forearm and upper arm. Moreover, the connection part of the robot was used as an elastic element instead of adding an extra element. The material of these linkage bars is steel with good rigidity performance. Within a certain deformation range, the deformation of the bar is proportional to the exerted force. By detecting the bending of these bars (linkage bar A and B in Fig. 2), the interaction force exerted on this robot can be calculated. The relationship between the exerted force and the deformation (shown in Fig. 2) can be calculated with Eq.1 on the precondition that the long bar keeps straight as a reference position.

$$F = K * \Delta H \tag{1}$$

Here K is a coefficient obtained with experimental method; ΔH represents the deformation of the elastic bar; F represents the exerted force to the robot.

The tiny bending is enlarged with a long bar so that the deformation of elastic bars can be more accurately detected with a sensor. In this paper, an optical mouse was used to detect the deformation of the long steel bar's end part. The optical mouse contains a small camera and a LED light. It has several advantages, such as, low friction, good linearity, and cheap.

In order to ensure the control accuracy, the elastic bar should return to the reference position after removing the exerted force. A simple test was carried out to verify the efficacy of proposed structure. In this test, the position of the long bar's end part was recorded with the optical mouse. The force was exerted on the end part of the long bar and then removing the force. Result (Fig. 3) proved that the long bar can return to the reference position with small error after removing the exerted force, also this structure can ensure the control accuracy well.

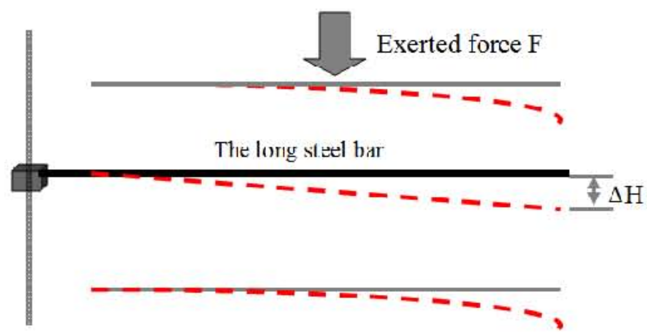


Fig. 2 Principle of interaction force detecting

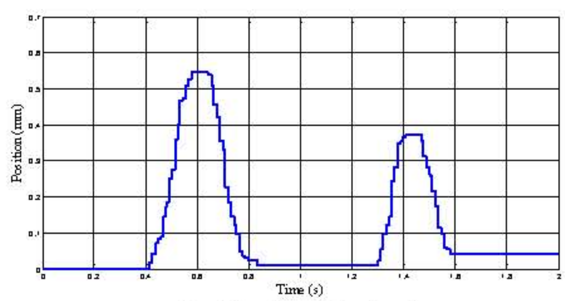


Fig. 3 Position of the long bar

III. Experiment and Results

To evaluate the efficacy of proposed structure, several experiments were conducted to exert three levels resistance using the device.

A. Control architecture

The whole system contains mainly three parts (Fig. 4), which are the force detecting part, PC interface, and the Digital signal processer (DSP2812). The force detecting part has been introduced in Part II. The PC was chosen as the upper computer, which can record the coordinate data of mouse and communicate with the DSP2812 (the lower computer) through the RS-232 protocol for conveying the recorded data and sending the coordinate data of mouse to DSP2812. DSP2812 has two functions. The first is used for generating two channels of pulse-width modulations (PWM), one was used for controlling the rotation speed of the steeping motor, and the other was used for controlling the rotation direction. The second is used for sampling the data from sensors with AD.

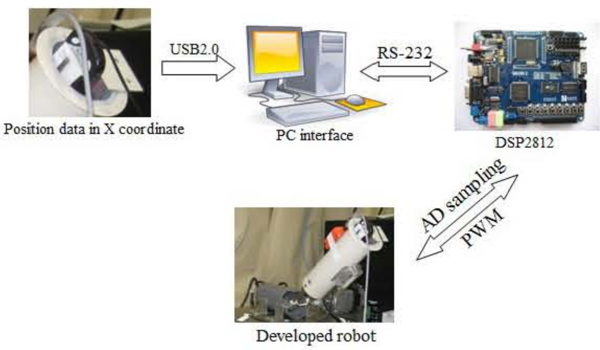


Fig. 4 The control architecture of the whole system

B. Experiment and Results

Three levels force were exerted on the robot's forearm part along the arrow direction showed in Fig. 5 separately. Different resistances were realized by changing the threshold set in program, under which there is no PWM output. After the optical mouse detect the deformation of the elastic bar until it larger than the threshold, the robot started to move. In order to maintain the resistance, the controller can regulate the frequency of PWM to maintain the deformation according to the Eq. 1.

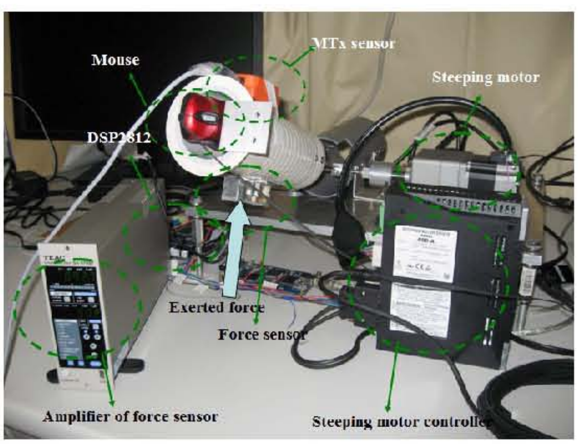
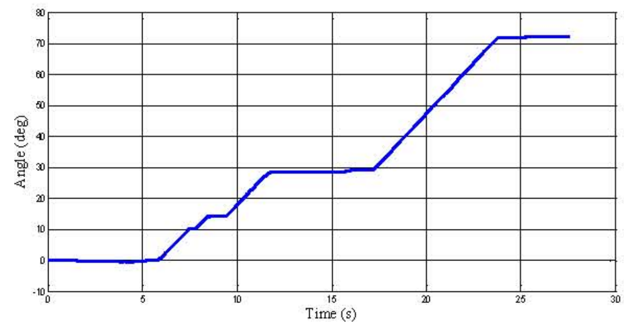
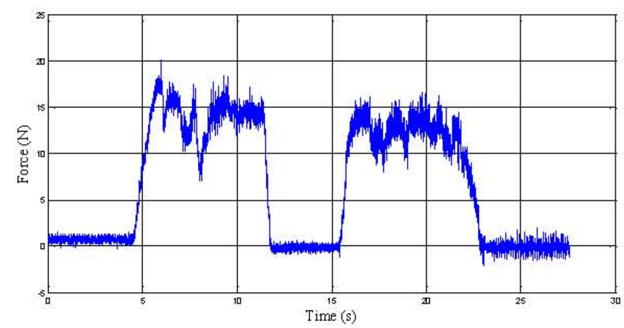


Fig. 5 Experiment setup

During the experiment, the interaction force was recorded with a strain gauge inside force sensor and amplified with an indicated amplifier. The pitch angle during the experiment was recorded with the MTx sensor. After three levels resistance experiments, three groups of results were obtained (from Fig. 6 to Fig. 8) which represent the low resistance experiment, medium resistance experiment and high resistance experiment separately. The principle of the proposed structure and control method can be explained from these results. It can be found that after gradually increasing the interaction force until it becomes larger than the threshold set in advance, the robot had a tiny deformation first and then start to rotate. The tiny deformation includes the deformation of the elastic bar and the upper limb itself. The interaction force could maintain a constant value and generate constant resistance. The robot stopped rotating when the interaction force was removed. These results recorded by the force sensor contain some noises, which come from the tremble of human's hand when exerting the force.

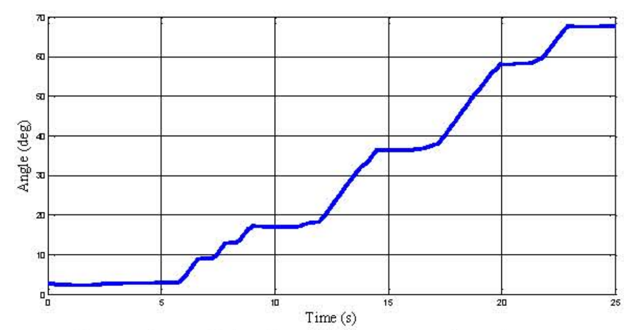


(a) Rotation angle (low resistance experiment)

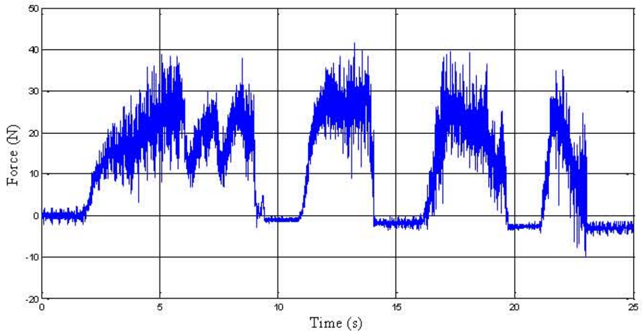


(b) Interaction force (low resistance experiment)

Fig. 6 Experimental result with low resistance

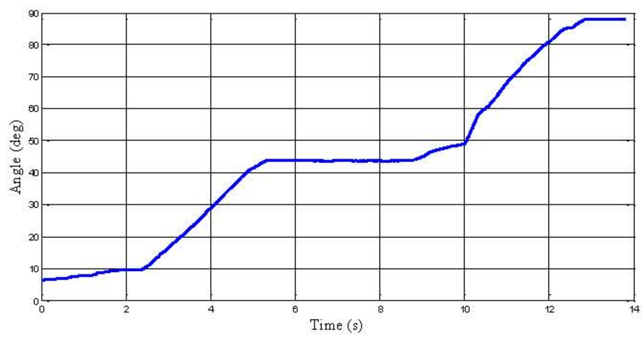


(a) Rotation angle (medium resistance experiment)

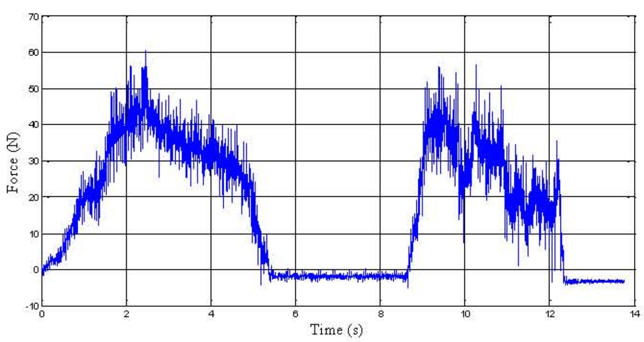


(a) Rotation angle (medium resistance experiment)

Fig. 7 Experimental result with resistance impedance



(a) Rotation angle (high resistance experiment)



(a) Rotation angle (high resistance e experiment)

Fig. 8 Experimental result with high resistance

IV. Conclusions and Future Works

In this paper, a human upper limb-like robot which can mimic the spasticity of stroke patient is proposed. The dimension and the range of movement were designed based on the real human's arm. However, the device is non-backdrivable, which decreases its operability. A new structure is proposed in this paper by adding two elastic bars to connect the robot's forearm and upper arm part. By detecting the bending of these bars, the interaction force exerted on this robot can be calculated. The tiny bending is enlarged with a long bar so that the deformation of elastic bars can be more accurately detected with an optical mouse. A simple test was carried out to verify whether the long bar can return to the reference position after removing the exerted force for ensuring the control accuracy. To evaluate the efficacy of proposed structure and control method, experiments were conducted to exert three levels resistance using the device. During these experiments, a train gauge inside force sensor was used to record the interaction force, and the MTx sensor was used to record the robot's rotation angle. Experimental results show that the proposed structure is effective, and the exerted resistance can be adjusted with it.

In the future, the robot should be made more robust and extend to more DoFs including the shoulder and hand. Limited with the manufacture of the robot and the measurement accuracy of the optical mouse, it is difficult to realize variable resistances. Therefore, the performance of the robot should be improved. And the final task is to perform the master-slave rehabilitation with the proposed master device and the upper limb exoskeleton rehabilitation device (ULERD) developed in our lab.

Acknowledgment

This research is supported by Kagawa University Characteristic Prior Research fund 2013.

References

[1] American Heart Association, "Heart disease and stroke statistics 2010 update: a report from the American Heart Association", Circulation, 121: e46-e215, 2010.

[2] J.D.Schaechter, "Motor rehabilitation and brain plasticity after hemiparetic stroke", *Progress Neurobiol.*, vol. 73, pp.61-72, 2004.

[3] H. I. Krebs, B. T. Volpe, M, L. Aisen and N. Hogan, "Increasing productivity and quality of care: Robot-aided neuro-rehabilitation", *Journal of Rehabilitation Research and Development*, vol. 37, no. 6, pp639-652, 2000.

[4] Rui Loureiro, Farshid Amirabdollahian, Michael Topping, Bart Driessen, William Harwin, "Upper Limb Robot Mediated Stroke Therapy – GENTLE/s Approach", Journal of Autonomous Robots, vol. 15, no.1, pp.35-51, 2003.

[5] Marco Guidali, Alexander Duschau-Wicke, Simon Broggi, Verena Klamroth-Marganska, Tobias Nef, Robert Riener, "A Robotic System to train activities of daily living in a virtual environment", *Medical & biological engineering & computing*, vol. 49, no. 10, pp.1213-1223, 2011.

[6] Zhibin Song, Shuxiang Guo and Yili Fu, "Development of an upper extremity motor function rehabilitation system and an assessment system", International Journal of Mechatronics and Automation, Vol.1, No.1, pp.19-28, 2011.

[7] Zhibin Song and Shuxiang Guo, "Design Process of Exoskeleton Rehabilitation Device and Implementation of Bilateral Upper Limb Motor Movement", *Journal of Medical and Biological Engineering*, Vo.32, No.5, pp.323-330, 2012.

[8] Minh Duc Duong, Chisato Teraoka, Takashi Imamura, Takanori Miyoshi, Kazuhiko Terashima, "Master-slave system with teleoperation for rehabilitation", *16th IFAC World Congress*, Th-A01-TP/9, 2005.

[9] Craig R. Carignan, Pontus A. Olsson, "Cooperative Control of Virtual Objects over the Internet using Force-Reflecting Master Arms", *Proceeding of the 2004 IEEE International Conference on Robotics & Automation*, pp.1221-1226, 2004.

[10] Matthew M. Williamson, "Series Elastic Actuators", *A.I. Technical Report*, no. 1524, 1995.

[11] Zhibin Song and Shuxiang Guo, "Study on Impedance Generation Using an Exoskeleton Device for Upper-Limb Rehabilitation", *Proceeding of 2012 IEEE International Conference on Multisensor Fusion and Integration for Intelligent System (MFI)*, pp.281-286, 2012.

[12] Zhibin Song, Shuxiang Guo, Nan Xiao, Liwei Shi, and Baofeng Gao "Sensor-based detection of human upper limb motion for human-machine synchronization control for active rehabilitation", *Sensors*, Vol. 12, No. 12, pp.16046-16059, 2012.