Development of Portable Rehabilitation Device Using Flexible Spherical Actuator with Built-in Embedded Controller and Valves

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***Abstract*—This study aims at developing a potable rehabilitation device which can be safe to use during holding it by both hands. In our previous study, a novel flexible pneumatic cylinder that can be used even if it is deformed by external force has been developed. A portable rehabilitation device using the flexible spherical actuator that consists of two ring-shaped flexible pneumatic cylinders was proposed and tested. In this paper, more portable and lower-cost rehabilitation device using the spherical actuator that includes the built-in embedded controller and valves is proposed and tested. The attitude control of the device using the built-in controller is executed. As a result, the portable rehabilitation device that it is possible to give the rehabilitation motions to patients with sequential control can be realized. The whole cost of the device can be reduced by a one-third.**

***Index Terms*—portable rehabilitation device, flexible pneumatic cylinder, flexible spherical actuator, embedded controller, low cost**

I. Introduction

In an aging society, it is required to develop a system to aid in nursing care [1] and to support the activities of daily life for the elderly and the disabled [2], [3]. In addition, the rehabilitation devices help the elderly who was injured temporally to recover their physical ability for keeping Quality of Life (QOL). The actuators used in such a system need to be flexible so as not to injure the human body [4]. The purpose of this study is to develop a portable rehabilitation device that can be safe enough to use it while handling it with human hands. In our previous study, a novel flexible pneumatic cylinder that can be used even if the cylinder is deformed by external forces has been proposed and tested [5]. We also developed a flexible robot arm and a spherical actuator using the flexible pneumatic cylinders, which can be used on a table as a rehabilitation device for human wrist and arm [6]-[8]. A portable rehabilitation device using the flexible spherical actuator that consists of two flexible pneumatic cylinders was proposed and tested. The flexible spherical actuator can create larger bending motion along the spherical surface. However, the tested device has many pressure supplied pipes and electric signal lines connected with the embedded controller and valves. In this paper, the development of more portable rehabilitation device will be described. In order to realize more portable rehabilitation device, it is necessary to unite the controller and valves into the flexible spherical actuator. This paper also described about development of not only portable device but also lower-cost device.

II. Previous Portable Rehabilitation Device

A. Flexible Pneumatic Cylinder

Fig. 1 shows the construction of a rod-less type flexible pneumatic cylinder developed by us [5]. The cylinder consists of a flexible tube as a cylinder and gasket, one steel ball as a cylinder head and a slide stage that can move along the outside of the cylinder tube. The steel ball in the tube is pinched by two pairs of brass rollers from both sides of the ball. The operating principle of the cylinder is as follows. When the supply pressure is applied to one side of the cylinder, the inner steel ball is pushed. At the same time, the steel ball pushes the brass rollers and then the slide stage moves toward opposite side of the pressurized while it deforms the tube.

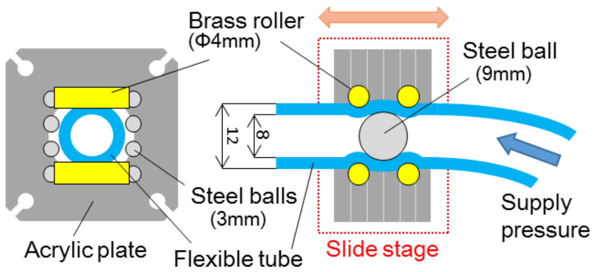

Figure 1. Construction of the flexible cylinder.

B. Flexible Spherical Actuator

Fig. 2 (a) shows the appearance of the previous spherical actuator. The actuator was developed as a rehabilitation device for shoulders and arms. It is imaged that patients will hold both handling stages, which are top and bottom stages in Fig. 2, by their both hands in the rehabilitation. Two slide stages of each flexible cylinder are not connected with one side base, that is, each slide stage of the flexible cylinder is fixed on each handling

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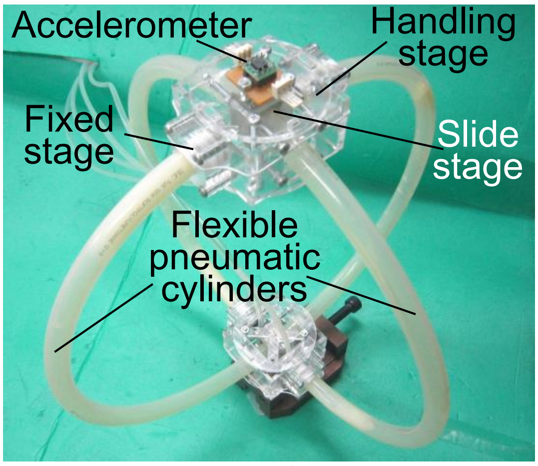
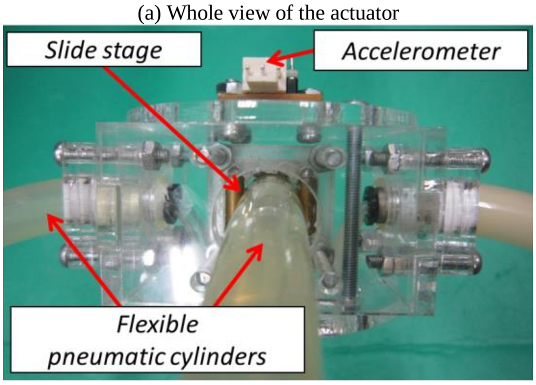
stage as shown in Fig. 2 (b). The size of the actuator is 260 mm in width and 270 mm in height. The total mass of the actuator is 310 g. In addition, to measure the attitude angle of each handling stage, two accelerometers are used as angular sensors.

Fig. 3 shows the transient view of the movement of the actuator. In the experiment, the sequential on/off operation of the control valve every 0.8 seconds was done. The supply pressure of 450 kPa is applied to the control valve. From Fig. 3, it can be seen that the device can create the different attitudes easily. We also observed that the device can work smoothly while the human holds it by both hands.



(a) Whole view of the actuator



(b) Detailed photo of the handling stage

Figure 2. Flexible spherical actuator.

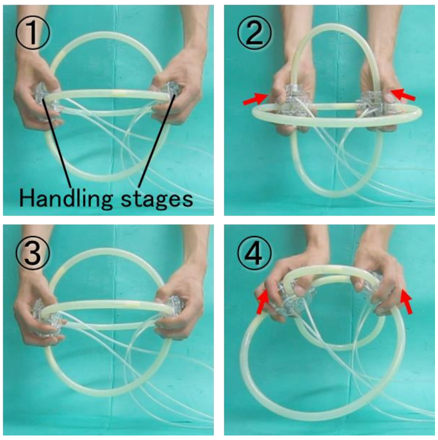


Figure 3. Transient view of the movement of the actuator.

C. Master-Slave Attitude Control System

The angular change θ, ψ and φ defined as shown in Fig.4 are given by the following equations, respectively [9]. Where, A_{xout}, A_{yout} and A_{zout} are incremental A/D values for x, y and z axes in the accelerometer.

$$\theta = \tan^{-1}\left(\frac{A_{xout}}{\sqrt{A_{yout}^{\ 2} + A_{zout}^{\ 2}}}\right) \tag{1}$$

$$\psi = \tan^{-1}\left(\frac{A_{yout}}{\sqrt{A_{xout}^{\ 2} + A_{zout}^{\ 2}}}\right) \tag{2}$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{A_{xout}^{\ 2} + A_{yout}^{\ 2}}}{A_{zout}}\right) \tag{3}$$

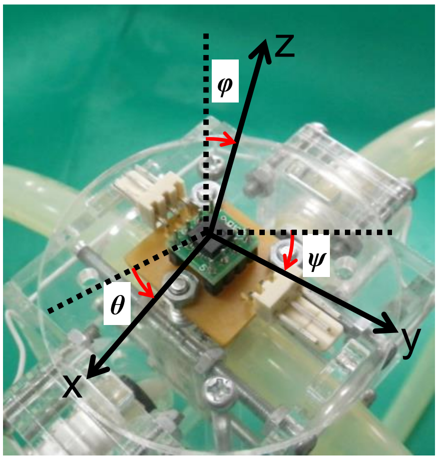


Figure 4. Attitude angle (θ, ψ and φ).

Fig. 5 shows the schematic diagram of the master-slave attitude control system of portable rehabilitation device. The control system consists of the improved spherical actuator with two accelerometers as a slave device, a master device with an accelerometer, four quasi-servo valves [10] to operate two flexible pneumatic cylinders and a microcomputer (Renesas Co. Ltd., SH7125) as a controller. The accelerometers were used as angular sensors of the master and slave handling stages. The attitude control of the device is done as follows. The desired angles between both stages are given by the sequential data or the master device operated by physical therapist. For measuring the master and slave stage's angles, the microcomputer gets the output voltages from each accelerometer. The angle between both handling stages in the slave could be obtained from the calculated angles of each stage. According to the deviation between the master's and the slave's angle, the quasi-servo valves are driven based on the control scheme, and the flexible pneumatic cylinders are driven. The sampling period of the control is 4 ms. The PWM period of the quasi-servo valve is 10 ms. Both the angular measuring of the devices and the attitude control could be realized by using an embedded controller. Fig. 6 shows the view of the attitude control system. The total mass of the system including the controller and the valves is small, about 0.9kg.

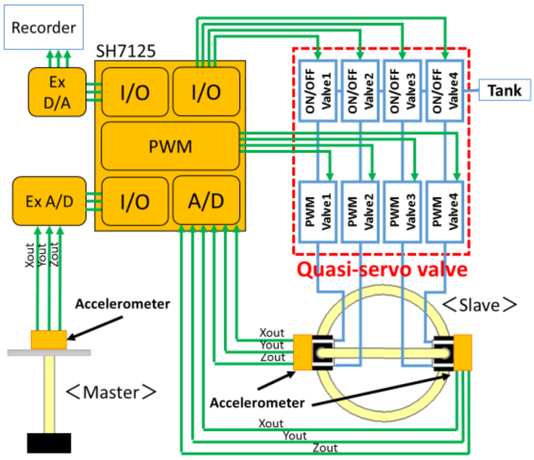


Figure 5. Attitude control system of the device.

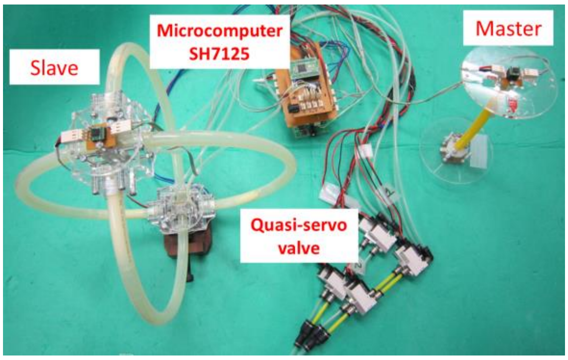
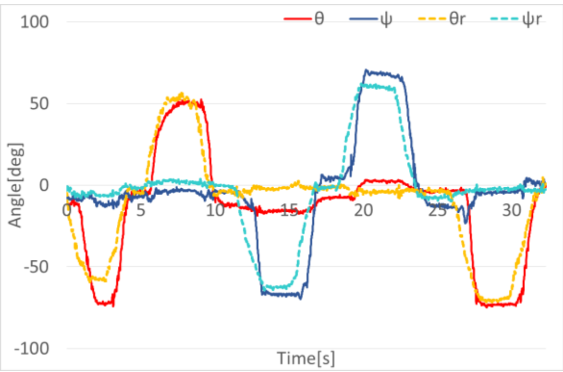
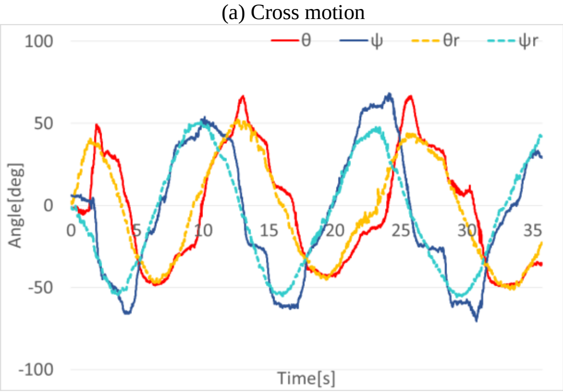


Figure 6. View of rehabilitation device with the attitude control system.



(a) Cross motion



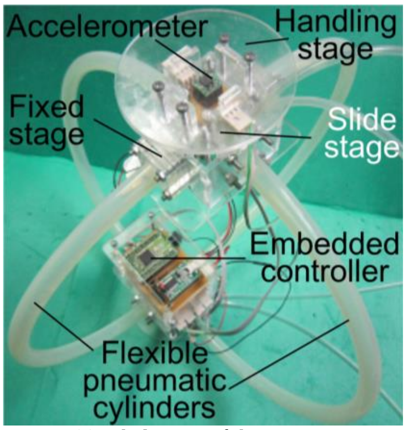
(b) Circular motion

Figure 7. Transient response of stage angle using master-slave control.

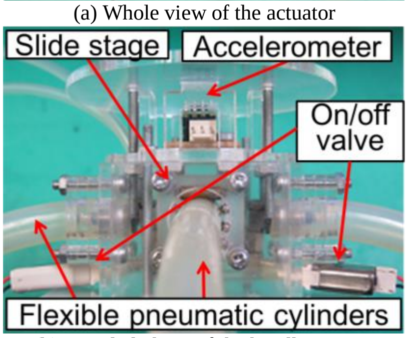
D. Control Results

A master-slave control using the system was carried out. Figs. 7 (a) and (b) show the transient responses of the angles of the stage in the device for a cross motion and circular motion, respectively. In both figures, broken lines show the desired angles (θ_r and φ_r) and solid lines show the controlled angles (θ and φ) of the slave device, respectively. From Figs. 7 (a) and (b), it can be also found that there is a little large error between the master and slave angles. These errors and overshoots will be reduced by using more robust control scheme and adjusting the control parameters.

The estimated cost of the device is about 330US$. The most of the whole cost is for four quasi-servo valves that includes eight on/off valves. The cost of the quasi-servo valves is about 270US$. It needs to decrease the whole cost of the device so that the patients can be easily used in their house. In addition, there are many electric signal lines and pneumatic supply pipes in the system. These lines prevent to give the comfortable rehabilitation for the patient. Therefore, it is necessary to unite these components to construct the more portable rehabilitation device.



(a) Whole view of the actuator



(b) Detailed photo of the handling stage

Figure 8. Improved portable rehabilitation device.

III. Improved Portable Rehabilitation Device

A. Construction

Fig. 8 (a) and (b) show the appearance of the improved portable rehabilitation device using the spherical actuator. In order to unite the embedded controller and valves into the rehabilitation device, it is necessary to increase the size of the spherical actuator to get enough space for the controller. Therefore, the diameter of the ring-shaped flexible pneumatic cylinder is changed from 260 mm to 290 mm. Two acrylic handles are installed on both handling stages to be easy to hold. In each handling stage has two small sized on/off valves (SMC Co. Ltd., S070C-SDG-32) that are connected with the flexible pneumatic cylinder. The controller that consists of three electric boards is set on the stage. The electric circuit board has the embedded controller (Renesas Co. Ltd., SH7125), a serial communication board and transistors. There is electric signal line between both handling stages to connect from the controller to the accelerometer. A pneumatic supply pipe is shared to four valves in the spherical actuator. By this improvement, the device only has a pneumatic supply pipe and two electric lines (Vcc and GND). The size of the actuator is 290 mm in width and 320 mm in height. The total mass of the device is light-weight, that is 580 g, even if the device has the whole pneumatic driving elements with controller. In addition, by decreasing the number of valves in the system and using the lower cost valves, the whole cost of the device can be decreased.

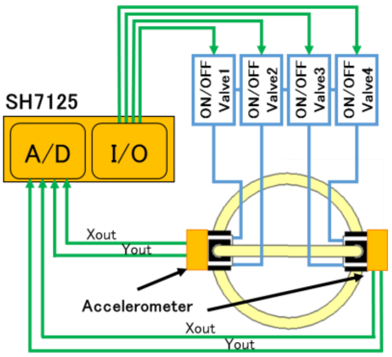


Figure 9. Control system of the improved portable rehabilitation device.

B. Control System

Fig. 9 shows the schematic diagram of the control system of the improved portable rehabilitation device. The control system consists of the improved spherical actuator with two accelerometers, four low-cost on/off valves to operate two flexible pneumatic cylinders and an embedded controller (Renesas Co. Ltd., SH7125). Compared with the previous system as shown in Fig. 5, the quasi-servo valve is changed to the typical on/off control valves. By this improvement, the estimated cost of valves is remarkable decreased from 270US$ to 60US$. The signal from two accelerometers is only used for monitor of angular change between both handling stages. The sequential control scheme is applied to the system. Therefore, the estimated cost of the controller can be reduced from 50US$ to 25US$ in the case that two accelerometers are not used as a monitor.

C. Experimental Result

Fig. 10 shows the transient view and the response of the stage angle of the improved portable rehabilitation device. In the experiment, the device was driven alternately to the direction of each flexible pneumatic cylinder as shown in Fig. 10. The supply pressure of 400 kPa was applied to the valve. From Fig. 10, it can be seen that the device can give the rehabilitation motion to the hands. Also, it can be seen that the device can measure the angle between both handling stages in the device by two accelerometers. These measured angles can be used for the attitude control the device. The estimated cost of the device can be reduced from 330US$ to 100US$ by using the low-cost valve. The total mass of the device is also decreased by a two-third, that is from 900 g to 580 g. As a result, more portable and lower-cost rehabilitation device can be realized.

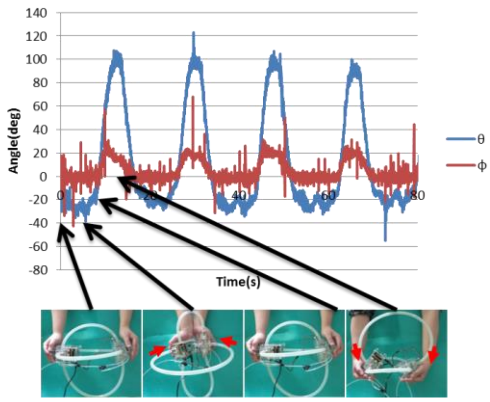


Figure 10. Transient view and response of the stage angle of the improved portable rehabilitation device.

IV. Conclusions

This study that aims to develop more portable rehabilitation device can be summarized as follows.

1) The portable rehabilitation device that unites the embedded controller and valves into the flexible spherical actuator was proposed and tested. In order to unite the controller, the electric circuit board with the embedded controller was redesigned. As a result, the total mass of the device can be reduced from 900 g to 580 g. By this improvement, a sum of the electric and pneumatic supply lines connected to the actuator from outside is also decreased from 14 to 3 lines.

2) By using the lower-cost on/off valve and reconstruction of the control system in the device, the total estimated cost of the device is reduced from 330US$ to 100US$. As a result, it is confirmed that the improved portable rehabilitation device can be applied to the home rehabilitation device from view point of its compact configuration and inexpensive cost.

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