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Development of Flexible Spherical Actuator Controlled by Low-Cost Servo Valve and Embedded Controller

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Abstract

A wearable actuator needs to be flexible so as not to injure the human body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be attached to the human body, and to apply it to a flexible mechanism and rehabilitation device. New types of flexible pneumatic actuator that can be used even if the actuator is deformed by external force have been developed in our previous studies. In this paper, we propose and test a flexible spherical actuator using the novel flexible pneumatic cylinders. The simple spherical actuator consists of two ring-shaped flexible pneumatic cylinders. They are intersected at right angle and are fixed on the base. The low-cost control system using the tested quasi-servo valves and an embedded controller (micro-computer) was also developed. The spherical actuator was also improved so as to suppress the vibration in control and to increase the stiffness of the actuator by changing the structure of the actuator. In addition, by using the quasi-servo valve controlled by the superior embedded controller, the flow rate of supply and exhaust could be controlled independently. As a result, the control performance could be improved using the improved spherical actuator and the quasi-servo valves controlled by the embedded controller with compensational method for exhaust.

Keywords: Spherical actuator; Flexible pneumatic cylinder; Quasi-servo valve; Embedded controller.

1. Introduction

Recently, it has been desired strongly to develop a system to aid in nursing care [1][2] and to support the activities of daily life for the elderly and the disabled [3]. The actuators required for 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 flexible and lightweight actuator and to apply it to a flexible robot arm, a rehabilitation device and so on. So far, new types of flexible pneumatic actuator that can be used even if the actuator is deformed by external forces have been proposed and tested in our previous studies [5]. Also, several kinds of rod-less type flexible pneumatic cylinder were tested, and the tested flexible pneumatic cylinder was utilized as a rotary actuator with one degree of freedom [6]. In the next step, it is desirable to apply this cylinder to a rehabilitation device. Therefore, we aim to develop a compact flexible actuator with multi degrees of freedom so as to use it on the table as a rehabilitation device for human wrist and arm. In this paper, we propose a flexible spherical actuator using the novel flexible pneumatic cylinders. The novel spherical actuator using two flexible pneumatic cylinders has a simple structure. By only driving two cylinders, the actuator can realize larger bending motion along to the spherical surface. An inexpensive bending control system using an embedded controller (a tiny micro-computer), accelerometers and the quasi-servo valve

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that consists of inexpensive on/off control valves is also proposed. In order to improve the control performance in this paper, we has develop the new design of the actuator. We also have embedded the master-slave control system into the new actuator for checking the control performance. We also aim to improve the tracking control performance of the bending control system by using the quasi-servo valve controlled by a superior embedded controller using PD control scheme with a compensational method of lower exhaust flow rate.

2. Flexible Pneumatic Cylinder

We have developed two types of novel rod-less type flexible pneumatic cylinder [6]. Figures 1 (a) and (b) show the constructions of the cylinder which (a) is a "Single ball type" and (b) is a "Double ball type". Both types have the similar construction and the same operating principle. The difference of their properties is that the single ball type has less frictional force, and the double ball type has higher flexibility. The single ball type cylinder consists of a flexible tube as a cylinder and gasket, one steel ball as a cylinder head and a slide stage that can slide along the outside of the tube. The steel ball is pinched by two pairs of brass rollers from both sides of the ball. The operating principle of the rod-less type flexible pneumatic 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 while it deforms the tube. We investigated the minimum driving pressure of the tested rod-less type flexible pneumatic cylinder using various center distance D (shown in Fig.1) and the distance W between two pairs of rollers as a design parameter. From the experiments, the optimal design parameters D of 14.4mm and W of 10mm were obtained [6]. The minimum driving pressure of the double ball type cylinder is 130kPa. This is a little higher than that of the single ball type, because the frictional force becomes larger due to the increase of the contact area between inner two balls and the inner bore of the tube. Furthermore, the double ball type cylinder is more flexible than the single ball type cylinder around the slide stage. It means that the single ball type cylinder has more stiffness by holding two pairs of the slide stage.

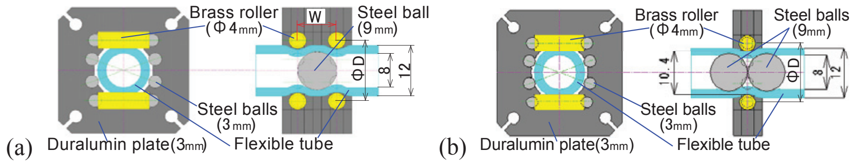


Fig. 1. Construction of rod-less type flexible pneumatic cylinder for (a) Single ball type and (b) Double ball type

3. Spherical Actuator

3.1. Construction

Figure 2 shows the construction of the tested spherical actuator. The actuator consists of two ring-shaped flexible pneumatic cylinders. It is intersected at right angle and is fixed on the base. In this actuator, the double ball type cylinders are used as a flexible cylinder so that the slide stage can easily move on the curved tube. The slide stages are connected each other with a crossing angle of 90 degrees. The diameter of each ring-shaped cylinder is 148mm and they can bend by being supplied the air to the cylinder. Two slide stages of each cylinders also are connected by a right angle so that the bending movement with 2 degree-of-freedom can be realized. The size of the actuator is 160 mm in width and 175 mm in height. The total mass of the actuator is 170g. The developed actuator can bend over the range of 240 degrees around the center of circle of the cylinder.

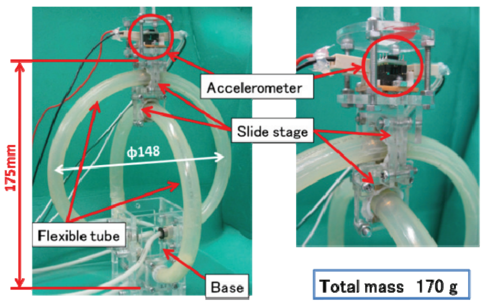
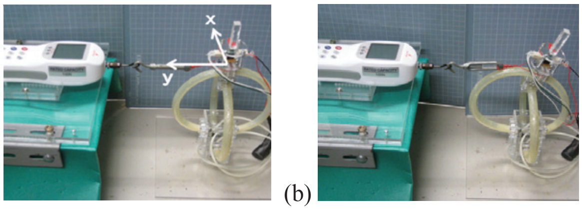


Fig. 2. View of tested spherical actuator

3.2. Fundamental characteristics

Figures 3 (a) and (b) show the experimental setup for measuring the generated force of the spherical actuator. In Fig.3 (a), the supply pressure is 0 kPa, and in Fig.3 (b), the supply pressure is 300 kPa. To measure the tensile force with force gauge the wire is fixed at a certain height of the actuator when the cylinder is pressurized. The measurement is carried out for four direction that is + or - x-direction and + or - y-direction. Here, x axis is taken in a parallel direction of the lower cylinder, and y axis is taken in a parallel direction of the upper cylinder. Figure 4 shows the relation between the generated force and the supply pressure. From Fig. 4, we can see that there exists a dead zone within + or - 100 kPa by the friction of the rod-less type flexible pneumatic cylinder. From Fig. 4, it can be also seen that the maximum generated force in x-direction is 3.5N, and the y-direction is 7N. The difference of the maximum force between x-direction and y-direction is caused by the fact that the wire-fixed point was the same in both directions as shown in Fig.3. Therefore, the torque is compared. Figure 5 shows the generated torque. It is calculated based on the distance from a circular center of the cylinder to the wire fixed point. The distance in x-direction is 105mm, and the distance in y-direction is 75mm. As a result, we can confirm that the maximum toque in x-direction is 0.36Nm and y-direction is 0.5Nm. This is because that the frictional toque of x-direction is larger than y-direction due to the longer distance from a circular center of the cylinder to the slide stage. Moreover, from a constructional point of view of the actuator, the posture in Fig. 2 seems to be the lowest stiffness for the actuator.



(a) (b)

Fig. 3. Experimental setup for measuring generated force for (a) Supplied pressure of 0 kPa and (b) Supplied pressure of 300 kPa

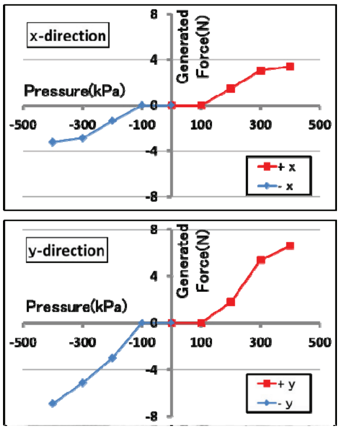


Fig. 4. Measured generated force

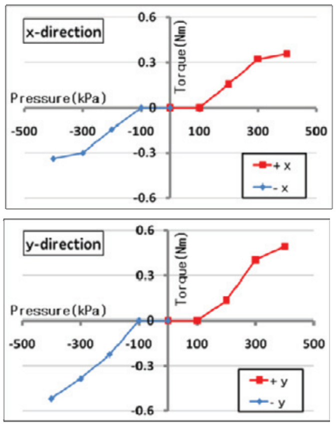


Fig. 5. Measured generated torque

3.3. Master-slave control system

Figure 6 shows the construction of the master-slave control system of the spherical actuator using accelerometers, and Fig. 7 shows the view of the system. The slave consists of the tested spherical actuator, an accelerometer, four quasi-servo valves to operate two flexible pneumatic cylinders and a low-cost micro-computer as a controller. The accelerometers were used as an angular sensor of the slide stage. The master-slave control is done as follows. The inexpensive embedded controller that is the micro-computer (Renesas Co. Ltd., H8/3664, clock frequency : 16 MHz, 3ch PWM ports with 16 bit timer) gets the output voltage from two accelerometers. By the control scheme based on the difference of the voltages, the quasi-servo valves are driven, the flexible pneumatic cylinders are driven and then the attitude of the spherical actuator is controlled. For the control scheme, the on/off control scheme and the PD control scheme were used. The master consists of an accelerometer for the desired attitude on the ring-shaped stage with a diameter of 100 mm as shown in Fig.7. The sampling period of the control is about 30 ms. Figure 8 shows the schematic diagram of the inexpensive quasi-servo valve which was developed in our laboratory [8]. The quasi-servo valve consists of two on/off control valves (Koganei Co. Ltd., G010HE-1) whose both output ports are connected each other. One valve is used as a switching valve to exhaust or supply, and another is used as a PWM (pulse width modulation) control valve that can adjust output flow rate like a variable fluid resistance. The valve connected with the actuator is a two-port valve without an exhaust port. Another is a three-port valve that can change the direction of fluid flow from the supply port to the output port or from the output port to the exhaust port. The two-port valve is driven by PWM method in order to adjust the valve opening per time. It becomes a quasi-variable orifice. Then, the latter valve is called as "PWM valve", and the former is called as "Switching valve". The size of the on/off valve is 33mm × 20mm × 10mm, and the mass is only 15g.

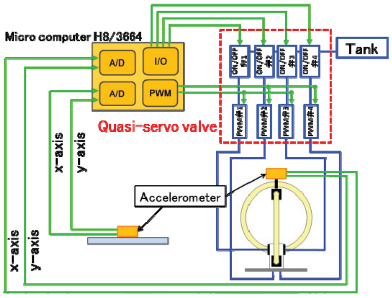


Fig. 6. Schematic diagram of control system

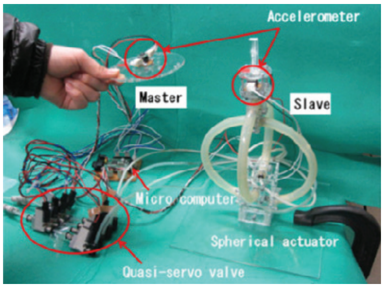


Fig. 7. View of master-slave control system

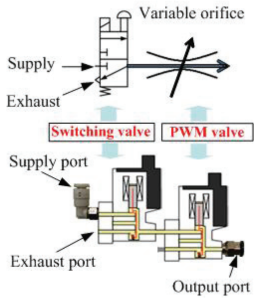


Fig. 8. Tested quasi-servo valve

3.4. Control scheme and experimental results

Figure 9 shows the transient response of the bending angles of the actuator using the on/off control scheme. In the experiment, the desired angles were given so as to rotate and bend the master device with a certain period. The upper figure shows the transient response of the bending angle of x-axis direction, the middle one shows the results of y-axis direction, and the lower one shows the result of the bending direction angle. The broken line shows the master, and the solid line shows the slave. From this figure, we can see that the bending angle and the bending direction angle of the slave have a larger oscillation compared with the master.

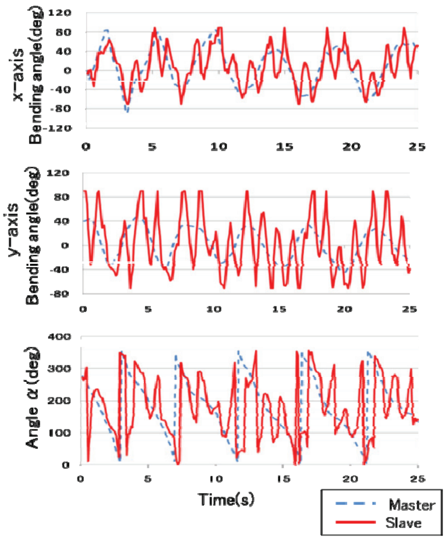


Fig. 9. Result using on/off control scheme

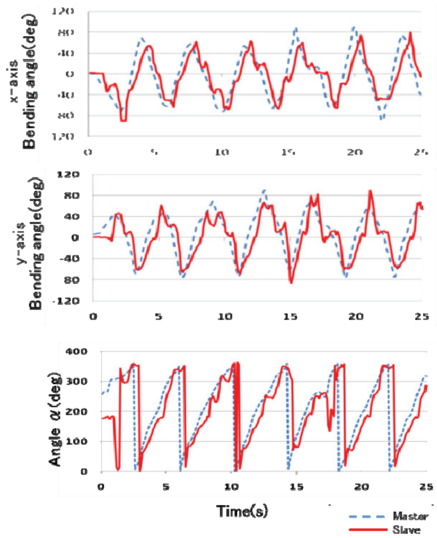


Fig. 10. Result using PD control scheme

Moreover, the accelerometer also detects an acceleration of the spherical actuator, and the result shows the larger change including the acceleration change than the real movement of the spherical actuator. This appears in the result of the bending direction angle such as larger angular change compared with the actual movement. It is caused by using the higher gain such as an on/off control scheme. Therefore, we need to apply the analogue control method in order to improve the control performance. In the experiment using PD control scheme, as a same manner of on/off control, the desired angles were given so as to rotate and bend the master device. The PWM period of the quasi-servo valve is 10ms. Figure 10 shows the transient response of each bending angle of the actuator using the PD control scheme. Figure 11 shows the view of movement of the actuator. Each figure in Fig.10 shows the result of the bending angle of x and y direction and the bending direction angle, respectively. From Fig.10, compared with on/off control result, the vibration of each angle became smaller. We found that the slave spherical actuator can trace the movement of the master device. However, it is needed to improve the control performance, because there is a step wise change of the slave bending angle. We think that it is caused by a lower stiffness of the spherical actuator. Therefore, it is necessary to improve the stiffness of the actuator.

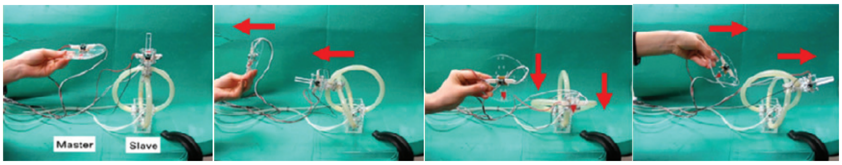
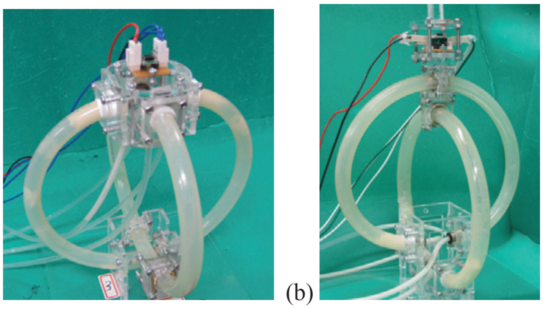


Fig. 11. View of master-slave control

4. Improvement of Spherical Actuator

4.1. Construction

The tested spherical actuator described above has a problem that it is easy to generate the vibration in the attitude control. The problem is caused by a lower stiffness of the slide stage in the actuator. In addition, the difference between generated torque of x and y direction caused by a gap in the slide stage will also induce the unbalanced movement. Therefore, an improvement of the spherical actuator is needed so that the actuator has a suitable stiffness. Figure 12 (a) shows the construction of the improved spherical actuator. Compared with the previous one as shown in Fig.12 (b), the top end and bottom end are changed reversely, that is, both ends of two cylinders are set on the same-leveled plane so as to construct a stage. On the other hand, two slide stages of the cylinders are set on the bottom stage. Each slide stage is set on the different acrylic plate of the base in order to decrease the gap at cross position of tubes. This gap is decreased from 30 mm to 12 mm. Each cylinder is also hold by an additional slider set on the opposite acrylic plate of the base that has a distance of 43 mm from the sliding stage. In addition, the single type rodless flexible pneumatic cylinders were also used in the actuator instead of the double type cylinder in the previous actuator. By this method, we aim to give the suitable stiffness to the actuator. The diameter of each ring-shaped cylinder is 160 mm. The size of the improved actuator is 160 mm in width and 170 mm in height. The total mass of the actuator is 300 g.



(a) (b)

Fig. 12. View of improved spherical actuator for (a) Improved type and (b) Previous type

4.2. Characteristics of generated torque

Figure 13 shows the relation between supplied pressure and the generated torque of the improved actuator. The measuring method is same as the pervious case as shown in Fig. 3. The torque is calculated from the measured generated force and radius of the improved actuator. The torque of x and y direction were calculated based on the distance of 85mm and 80 mm from the center of each ring-shaped cylinder to a fixed position of the force sensor, respectively. From Fig.13, it can be seen that the maximum generated torque in the x direction is 0.45 Nm and the y-direction is 0.47 Nm. The difference between two values could be reduced compared with the previous case that is 0.36 Nm in x direction and 0.5 Nm in y direction. The improved actuator has a same dead zone of the generated torque for supplied pressure as the previous one. This is due to a minimum driving pressure of the flexible pneumatic cylinder. Furthermore, the characteristics is not linear compared with the previous. This is caused by a larger friction between the tube and slide stage by adding the additional slider on the base.

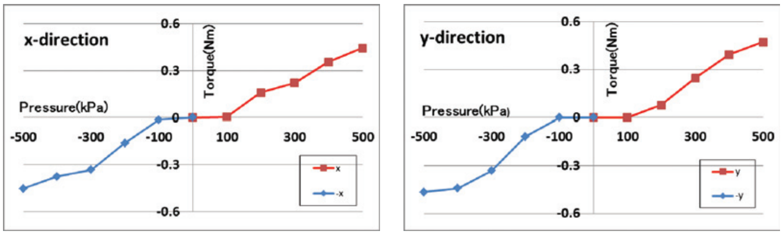


Fig. 13. Generated torgue of improved actuator

4.3. Master-slave control system using improved actuator and superior embedded controller

Figure 14 shows the schematic diagram of the master-slave control system using the improved spherical actuator and a superior embedded controller. Figure 15 shows a view of the tested control system. Compared with the previous system, the improved system used the superior type micro-computer (Renesas Co. Ltd., SH7125, Clock frequency: 50 MHz, 8 ch PWM ports with 16 bit timer). The sampling period is improved from 30 ms to 2.3 ms. In addition, each PWM control valve in quasi-servo valve is controlled independently by increasing the channels of PWM port. By using this method, the flow rate for each chamber of the cylinder can be controlled independently. It also means that the flow rate in the case of supply and exhaust can be changed for each chamber of the cylinder. It might be useful to improve the dynamics of the pneumatic actuator, because air in the opposite chamber of the double acting type cylinder prevents to drive the cylinder faster when one side of chamber is pressurized. The same PWM period of 10 ms is used for the quasi-servo valve. The control method is same as previous system mentioned before. The experimental results such as bending angles are measured by the recorder (Graphtec Co. Ltd., GL200) through the SPI communication type D/A converter (Linear Technology Co. Ltd., LTC1660).

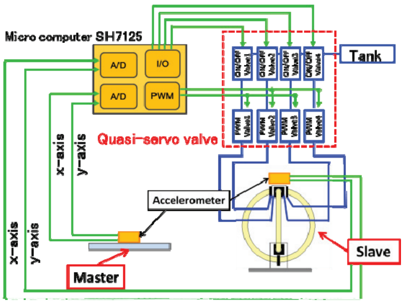


Fig. 14. Schematic diagram of improved control system

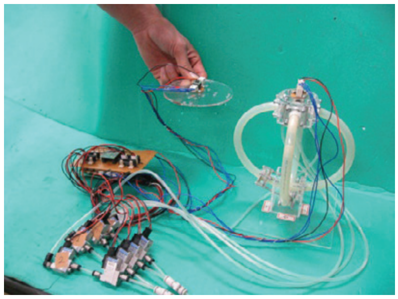


Fig. 15. View of master-slave control system

4.4. Experimental results

Figures 16 (a) and (b) show the transient response of the bending angles of the actuator using the improved actuator with PD control scheme. In Fig.16, the upper figure shows the transient response of the bending angle of x direction, the lower one shows the results of y direction. The broken line shows the master, and the solid line shows the slave. Figure 16 (a) shows the result using the ordinal PD control scheme as shown in Fig.10. Figure 16 (b) shows the result using PD control scheme with consideration for exhaust. In the experiment, as the compensation for exhaust, the input duty ratio for exhaust chamber of the cylinder is given double value that calculated by PD control scheme. From Fig.16 (a), the tracking performance of the bending angle can be improved by using the improved actuator and the superior embedded controller compared with the previous results as shown in Fig.10. Furthermore, compared with Fig.16 (a) and (b), it can be seen that the response of the bending angle with compensation becomes faster. Especially, compared with the tracking error of the bending angle, the standard deviation of the error can be reduced from 22.6 degrees to 18.4 degrees in the response of y-directional bending angle. It means that the dynamics of the control system can be improved by using the proposed compensational method.

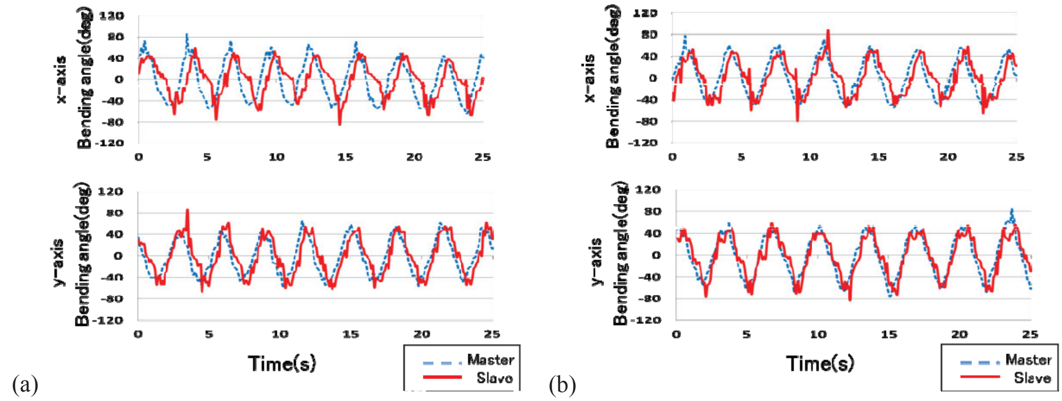


Fig. 16. Results using the improved actuator for (a) Without compensation for exhaust and (b) With compensation for exhaust

5. Conclusions

This study aiming at developing the compact flexible actuator with a larger moving area for rehabilitation device that can be used on a table is summarized as follows.

The simple-structured spherical actuator that consists of two flexible pneumatic cylinders was proposed and tested. The inexpensive master-slave control system using the tested actuator, four quasi-servo valves and a micro-computer was also proposed and tested. As a result, the control performance of the actuator could be improved by using PD control method and quasi-servo valves compared with the results using on/off control scheme.

In order to improve the control performance of the tested actuator, the improved actuator by changing the configuration of two flexible pneumatic cylinders was proposed and tested. As a result, the unbalanced characteristics of generated torque between x and y direction was improved.

The master-slave control system using the low-cost superior micro-computer was also developed. As a result, the sampling period could be reduced. The control performance of the improved actuator was also investigated using the improved controller. As a result, the tracking control performance of the actuator can be improved. In addition, the compensational method for the dynamics of the control system considering the property of the pneumatic valve and cylinder was proposed and tested. As a result, the standard deviation of the tracking control error can be reduced from 22.6 degrees to 18.4 degrees.

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