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Development of Active 80-faced Polyhedron for Haptic Physical Human-Machine Interface

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***Abstract*—The goal of this research is to realize a new type of physical human-machine interface. In this research, Active Polyhedron can treat virtual three dimensional continuums having many force output points. Active 80-faced Polyhedron can treat virtual objects that are more complex than Active Icosahedron which was previously developed. Towards realizing the overall hardware parts, 120 pieces of new and compact intelligent pneumatic cylinder with length measurement and communication function are designed and constructed. Communication and control system to control input-output data between PC and 120 cylinders was confirmed.**

Three experiments were carried out, which are position control of the cylinder, shape input experiments and spring motion experiments. In the shape input experiments, inputting shape information of the Active 80-faced Polyhedron to PC is realized. On the other hand, the spring motion experiments establish the stiffness function by changing stiffness coefficient of each intelligent cylinder where the operator can feel its difference. Both experimental results show the effectiveness of the Active Polyhedron for a new human machine interface.

I. INTRODUCTION

HAPTIC is the science of applying tactile sensation to human interaction with computers which relates with virtual reality. Among current available virtual tools, the haptic interface is at the cutting edge of technology [1]. Many field of research applies haptic interface which includes medical, manufacturing and entertainment for assisting human in designing and etc. For instance, cranial implants was designed in a PHANToM-based haptic environment using direct fabrication through electron beam melting technology [1] and robot path planning based on virtual tele-operation was done using haptic-aided tools [2].

Most of developed haptic interfaces are concentrated model that performs force-presentation on only one or a few points. For example, PHANToM [3] applies haptic interface in the concentrated model. The example of developed distributed model that perform force-presentation on many points is still fewer in compared with concentrated model. For instance, distributed physical human machine interaction was proposed as tool for chair design process which applies pneumatic cylinder as actuator for data input and output response [4]. In certain cases, the concentrated model is also insufficient in respects of numbers of force-presentation point and degree of freedom to realize virtual 3D to be applied to continuous objects in reality world.

Therefore, the purpose of this research is to realize a new physical human-machine interface which can exchange distributed information of force and deformation between human and machine using of distributed model to many force-presentation points.

Figure 1 shows the concept of the physical human-machine interface where human as the user will deform shape of the interface and machine will gives force responds according to designated function. By using this haptic devices, the user can not only feed information to the computer but can receive information from the computer in the form of a felt sensation on some part of the interface body.

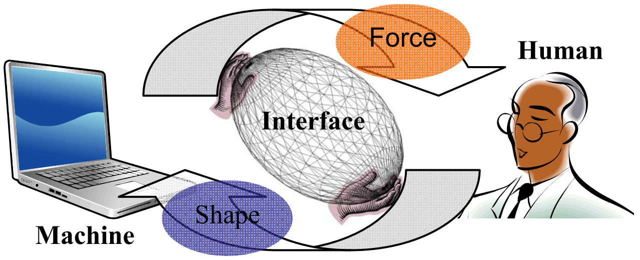

Fig.1 Concept of Physical Human-machine Interaction

We have developed a new type of haptic interface named Active Polyhedron which consists of intelligent actuators and spherical joints. Active Polyhedron is able to perform many force-presentations on apexes by controlling all intelligent actuators.

In previous researches, algorithms for treating multi-DOF 3D objects [5, 6] were discussed, but there have been no real mechanisms which simulates the motion of 3D continuous elastic bodies. We have developed in the previous papers [7-11] Active Tetrahedron and Active Icosahedron. Active Tetrahedron is an interface with 4 force-presentation points and 6-DOF while Active Icosahedron has 12 force-presentation points and 30-DOF.

In this report, Active 80-faced Polyhedron that have 42 force-presentation points and 120-DOF is developed to treat more complex virtual 3D continuous objects compared to the

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previous version of active polyhedron. To construct the Active 80-faced Polyhedron, 120 intelligent cylinders are needed. Thus, the new intelligent cylinder which is compact with high stroke and performance is designed and constructed. Communication control system is designed for controlling the Active 80-faced Polyhedron. Three basic experiments are carried out for confirming the human machine interaction which are position control, shape input and spring motion.

II. MECHANICAL DESIGN OF ACTIVE 80-FACED POLYHEDRON

A. *Structure of Active 80-faces polyhedron*

The structure of Active 80-faced Polyhedron consists of combination of the active link mechanism which based regular polyhedron shape. Only five kinds of regular polyhedron shape can be adopted for the Active Polyhedron. Active Icosahedron which has been developed has maximum force presentation points using regular polyhedron. Therefore a new shape of Active 80-faced Polyhedron can be developed from division of Icosahedron structure as in Fig.2.

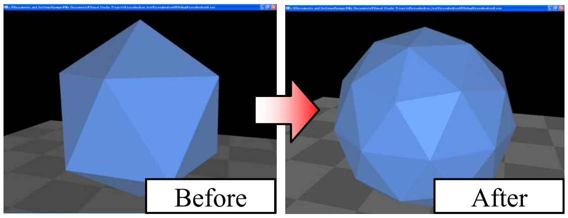
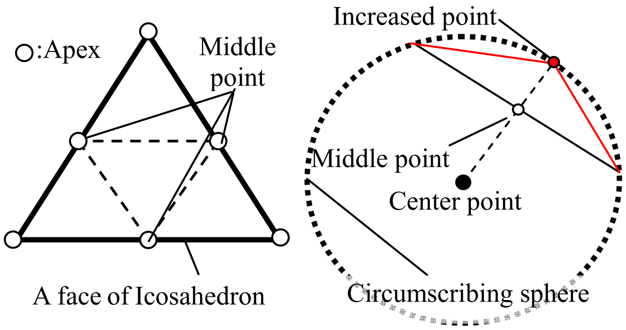


Fig.2 80-faced Polyhedron shape

The construction procedure of 80-faced polyhedron shape is shown in Fig.3: (a) First, one triangle of Icosahedron surface is selected. 4 surfaces and 6 apexes are created by connecting each middle point of triangular sides. (b) Next, each middle point is connected to center point of the Icosahedron. A new point for 80-faced polyhedron is the intersection point of the extended line with the circumscribing sphere of Icosahedron. The above-mentioned method is applied to all surfaces of Icosahedron.



(a)Division of triangle (b) Increasing of new apex

Fig.3 The method of increasing face

To control the Active 80-faced Polyhedron shape, it depends on the cylinder length and numbers of degree of freedom. The Active 80-faced Polyhedron can have multiple shapes which are unique from each other. The condition can be obtained from a geometrical analysis of degree of freedom. Generally speaking, degree of freedom of a mechanism is shown as follows:

$$f = 6(n-1) - \sum_{i=1}^{5} (6-i) p_i \tag{1}$$

where f represents degree of freedom of the mechanism, n represents the number of machine elements and p_i represents the number of pairing elements that have i degree of freedom. The Eq. 1 is applied to the structure of Active 80-faced Polyhedron.

Before applying the equation to Active 80-faced Polyhedron, certain assumption are considered as follows: (1) a joint of each apex consists of spherical joints, (2) one of the spherical joints is fixed to the base and does not move, (3) the joint corresponding to the each apex is small enough to neglect its mechanical play, and (4) an Active Polyhedron consists of liner actuators with one DOF paring elements.

The number of machine element that Active 80-faced Polyhedron has 240 because Active 80-faced polyhedron consists of 120 pneumatic cylinders with two driving mechanism. The number of one DOF paring elements, P_1, is 120 which represent one degree of freedom movement of the cylinder. The number of three DOF paring element, P_3, which comes from spherical joint's DOF, is 198 in total. Pairing elements with 2, 3 and 5 DOF, P_2, P_4 and P_5 is zero in this 80-faces Active Polyhedron.

Applying these numbers to Eq. 1, the degree of freedom of the mechanism, f is 240. 120 of the 240 DOF are from the spherical joint's rotation around the axis of the cylinder. They have no effect on the shape of Active 80-faced Polyhedron. The balance of 120 DOF comes from expansions and contractions of the 120 cylinders. Therefore the shape of Active 80-faced Polyhedron shape can be controlled uniquely by the length of each intelligent cylinder.

B. *Intelligent cylinder*

In the development of Active 80-faced Polyhedron, 120 actuators are needed for compact and high ratio of expansion and contraction. We have developed a new compact intelligent pneumatic cylinder which has a communication

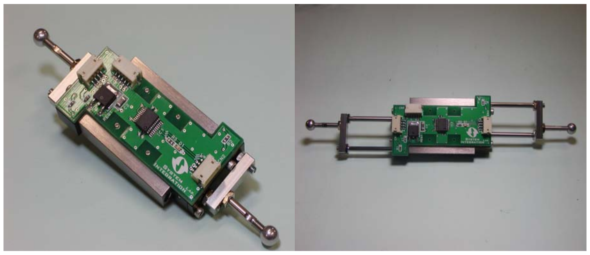


Fig.4Developed intelligent cylinder

TABLE I
COMPARISON OF PREVIOUS CYLINDER [10] WITH NEW CYLINDER

Details	New cylinder	Previous cylinder
Minimum length [mm]	113	133
Maximum length [mm]	169	173
Stroke [mm]	56	40
Position detecting resolution [mm]	0.0423	0.0845
Output force [N]	7.5	5
External output	I^2C	A,B signals

and control function ability. The developed cylinder is shown in Fig.4 and comparison with previous cylinder is shown in Table 1. The cylinder's length is 113 mm and it stroke is 56mm giving the ratio of expansion and contraction of 49.6 %.

The model of the intelligent cylinder structure is shown in Fig.5 where friction is ignored. The intelligent cylinder has 4 chambers for realizing high ratio of expansion and contraction. It can be driven by applying air pressure to each chamber. From the figure, the a_1 and b_1 are chambers for expansion and the a_2 and b_2 are chambers for contraction. The a_1 and b_1 chambers are connected by mechanical design. The a_2 and b_2 chambers also follow the same structure. Therefore the intelligent cylinder can be controlled by supplying the air pressure to two ports (a_1 and b_1). This method is the same as a general double-acting cylinder driving method.

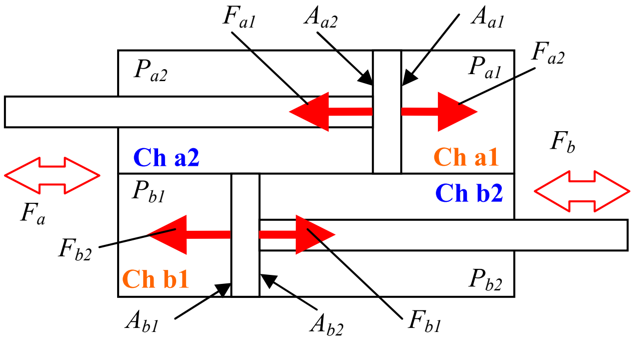


Fig.5 Structure of intelligent cylinder

Method of supplying air pressure to the intelligent cylinder is discussed as follows. The output force of the intelligent cylinder is presented in Eq. 2:

$$F_a = P_{a1}A_{a1} - P_{a2}A_{a2}$$
$$F_b = P_{b1}A_{b1} - P_{b2}A_{b2} \tag{2}$$

where F_a, F_b represent output force, P_{a1}, P_{a2}, P_{b1}, P_{b2} represent pressure in each chamber and A_{a1}, A_{a2}, A_{b1}, A_{b2} represent piston area in each chamber. From the above equation, the movement of the cylinder can be controlled by supplying air pressure to each chamber. The piston area of the intelligent cylinder is shown as follows:

$$A = A_{a1} = A_{b1} = 2A_{a2} = 2A_{b2} \tag{3}$$

where A represents constant area. By combining Eq. 2 and 3, output force is shown as follows:

$$F_a = A(P_v - 0.5P_c)$$
$$F_b = A(P_v - 0.5P_c) \tag{4}$$

where P_c is constant pressure (P_{a2}, P_{b2}) and P_v is variable pressure (P_{a1} and P_{b1}). P_c is supplied for contraction and P_v is for expansion. Therefore, if P_v can be controlled within the range from 0 to P_c, the motion control of the intelligent cylinder can be achieved. Thus, the range of the output force can be shown as follows:

$$-0.5AP_v \leqq AP_v \leqq 0.5P_v \tag{5}$$

The intelligent cylinder realizes length measurement function to detect guide rod stripes by an optical encoder. Fig.6 shows the stripes on the rod surface. The stripes are colored using YAG laser with a pitch of 0.169 mm.

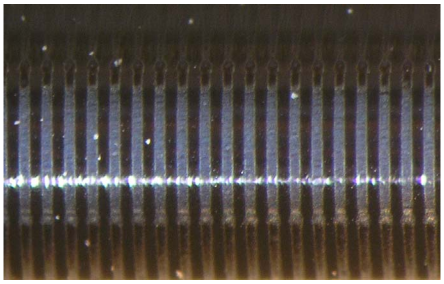
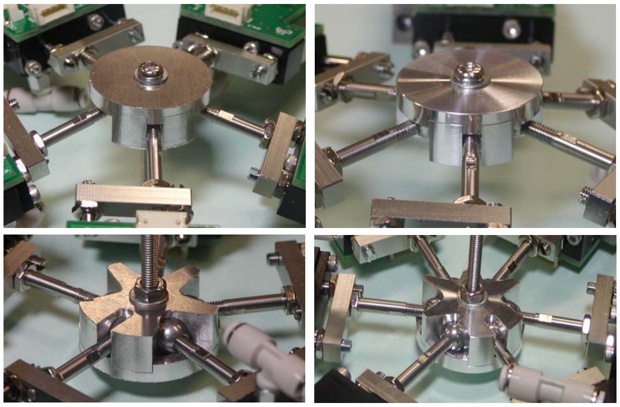


Fig.6 Surface of a guide rod with strip laser

C. *Spherical joint*

Two types of spherical joints are developed for constructing Active 80-faced Polyhedron. Figure 7 shows the spherical joints with multi degree of freedom. The 5-links joint connects 5 cylinder links and have nine DOF. The 6-links joint which connects 6 links have eleven DOF. Their joints consist of aluminum balls and plates. The balls are mounted on each end of links, enabling free-motion to every direction. Motion range of the joint is -45≦θ≦45 in horizontal direction and 0≦θ≦-90 in vertical direction. Each link joints have 1 link which is fixed with one DOF.



(a) 5-link joint (b) 6-link joint

Fig.7 Developed link joints

D. *Assembling of Active 80-faced Polyhedron*

Assembled Active 80-faced Polyhedron is shown in Fig. 8 with 120 intelligent cylinders and 42 link joints. Fig. 8 (a) shows the minimum size of the structure when each cylinder is in its minimum length of 113 mm. An example of Active 80-faced Polyhedron possible shape is shown in Fig.8 (b). It is possible to transform into various shapes by changing each cylinder length. The overall characteristics of the Active 80-faced Polyhedron are shown in Table II.

TABLE II
CHARACTERISTICS OF ACTIVE 80-FACED POLYHEDRON

Characteristics	Details
Minimum size [mm]	539
Maximum size [mm]	836
weight[kg]	8
Degree of freedom	120

(a) Minimum size shape (b)Transformed shape

Fig.8 Active 80-faced Polyhedron

III. DESIGN OF ACTIVE 80-FACED POLYHEDRON CONTROL SYSTEM

A. *Outline of Active 80-faced Polyhedron System*

The configuration of Active 80-faced Polyhedron system is shown in Fig.9. It consists of Active 80-faced Polyhedron, communication control system, ON/OFF valves and a PC. Communication control system is needed to control Active 80-faced Polyhedron from PC. PC can receive 120 displacement data of intelligent cylinders and control 120 valves by PWM through this system. The valves and each intelligent cylinder are supplied with air pressure which is compressed by the air regulator. The valves will drive the Active 80-faced polyhedron by receiving PWM cycles from the communication control system.

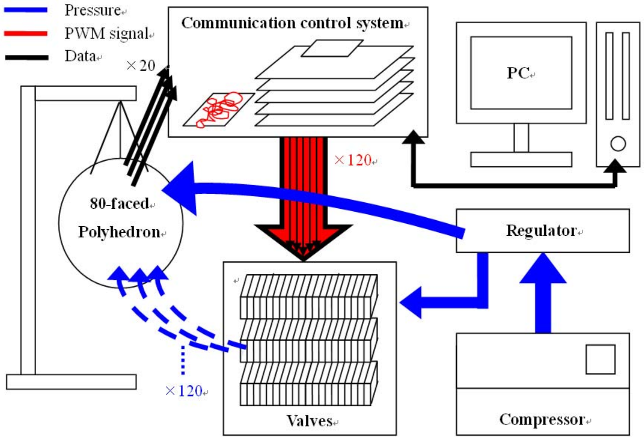


Fig.9 System of Active 80-faced Polyhedron

B. *Communication Control System*

Figures 10 and 11 show the developed communication control system and its configuration, respectively. The system applies three communication protocols which are USB, SPI and I^{2}C and controlled by PSoC chip. A USB circuits and five Multi communication circuits are aligned together in the system. The USB circuit mounts USB module (MINI EZ-USB FX2) which conducts USB communication with PC. USB PSoC then conducts SPI communication with the five Multi communication circuits. The Multi communication circuit equipped with one unit of Com_PSoC and four unit of S_PSoC. Com_PSoC treats SPI communication and S_PSoC controls the cylinders. The S_PSoC receives displacement data from six cylinders by I^{2}C communication and sends PWM signal to six valves to control the movements. Therefore 120 cylinders can be controlled by having 5 Multi communication circuits. The response speed of 15msec and data error rate less than 0.0137% are achieved using this communication control system.

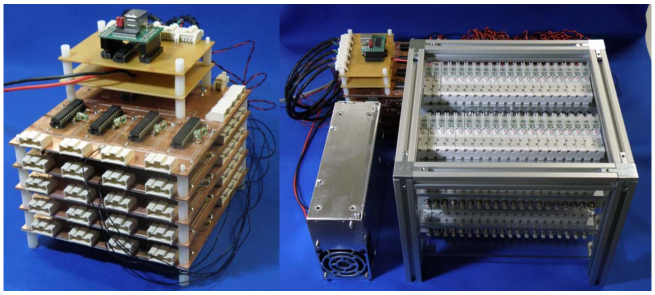


Fig.10 Developed communication control system

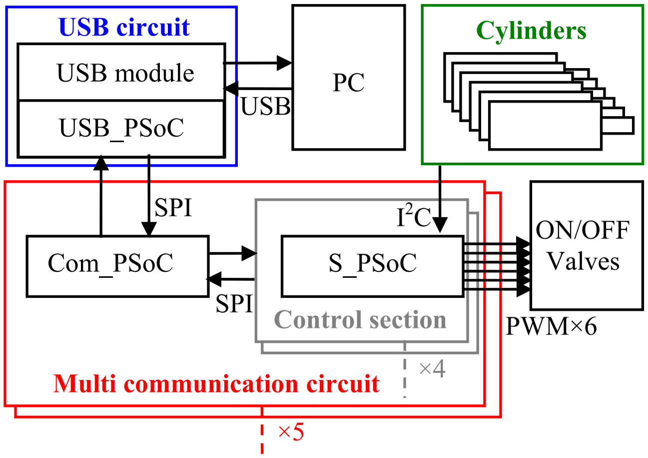


Fig.11 Configuration of Communication Control System

C. *Communication Device for Intelligent cylinder*

The system of Communication control device for a compact intelligent cylinder is shown in Fig.12. It has a PSoC (Cypress, CY27243-PXVI), two optical encoders (AVAGO technologies, AEDR-8300) and a LED. Counter modules in PSoC detect signals of encoders and I^{2}C module sends length data of cylinder to external device. The I^{2}C is a communication protocol which can communicate with two or more slave devices using only two communication lines. Therefore the electrical wiring in the interface system has been minimized to four lines including VCC, power and GND, ground using this communication.

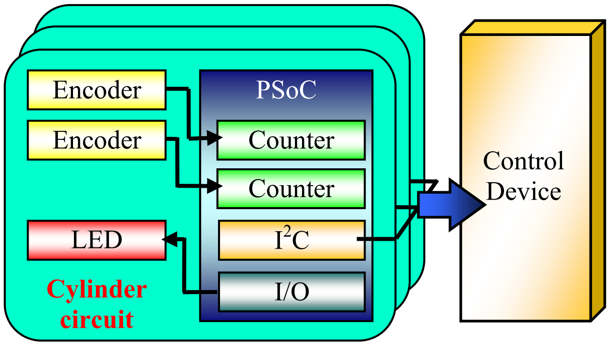


Fig.12 System diagram of compact intelligent cylinder

D. Kinematics & Dynamics

In this report, two basic algorithms are applied to Active 80-faced Polyhedron for realizing Physical Human Machine Interaction.

1) Shape input: The shape input algorithm will receive the length data from Active 80-faced Polyhedron and construct the deformation in PC. The forward kinematics of Active 80-faced Polyhedron decides the each apex positions by the link lengths of the intelligent cylinders. The forward kinematics is based on a structural feature of the triangle surfaces shape. The basic principle of the algorithm is shown in Fig.13 where one triangle apexes are $\boldsymbol{P}_1$, $\boldsymbol{P}_2$ and $\boldsymbol{P}_3$. The links are A, B and C. The initial lengths of links are L_a, L_b and L_c.

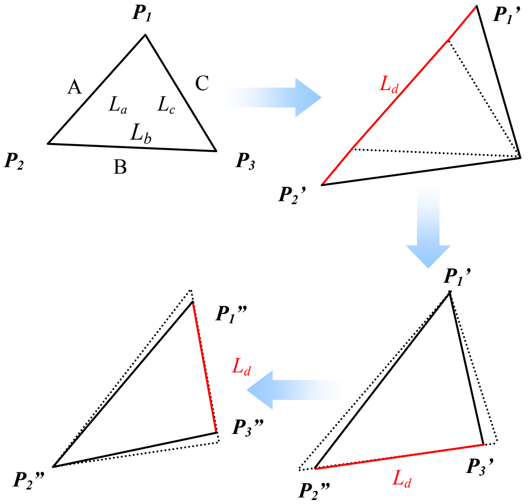


Fig13 Algorithm to get apex positions

The algorithm calculates each apex position by an iterative calculation process. Equations (6), (7) are fundamental equations, where n is varied in the order of n = 1, 2, 3, 1, 2.

$$P_n' = P_n + \frac{(P_n - P_{n+1})(L_d - L)}{2L} \tag{6}$$

$$P_{n+1}' = P_{n+1} + \frac{(P_{n+1} - P_n)(L_d - L)}{2L} \tag{7}$$

Applying the equations to link A, new apex positions of $\boldsymbol{P}_1$' and $\boldsymbol{P}_2$' are obtained from $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$. Applying the same method to Link B and C, $\boldsymbol{P}_1$'', $\boldsymbol{P}_2$'' and $\boldsymbol{P}_3$'' are obtained. Lengths of links approach target lengths by continuing this process to all links. When error of length is less than an acceptable value, this calculation process is finished.

2) *Spring motion*: Active 80-faced Polyhedron can be expressed as various elastic bodies by applying this algorithm. The model of one apex in the algorithm is shown by Fig.14. Applying the model to each cylinder, elastic force can be output from the apex. Output force of each cylinder model, F is obtained by following equation:

$$F = kx \tag{4}$$

where k and x represent stiffness coefficient and displacement of a cylinder in the model, respectively. Various elastic bodies are expressible by changing the stiffness coefficient.

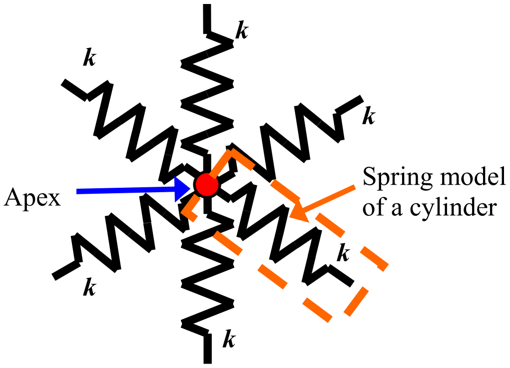
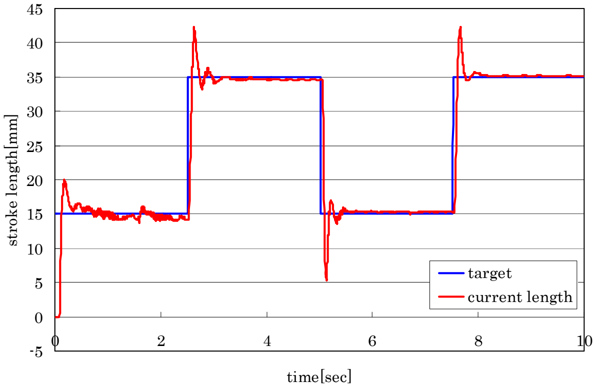


Fig.14 Model of Spring motion

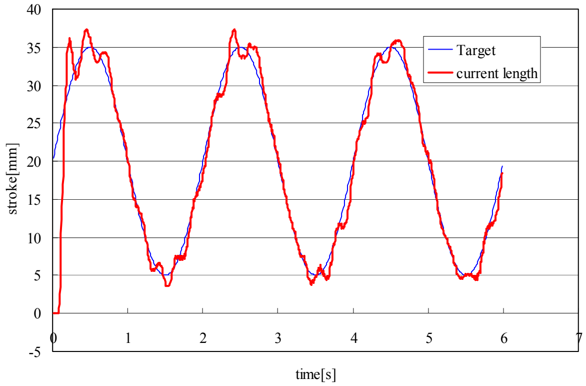
IV. EXPERIMENT

A. Evaluation test of the Intelligent Cylinder

A position servo control experiment is carried out as a performance evaluation test of developed intelligent cylinder. The experiment result comparing target value and observed value is shown in Fig.15. The vertical axis is cylinder length and the horizontal axis is time. As a result, the overshoot of about 7.5 mm was observed. For having faster response, the system has to compensate with certain overshoot value which is still small with high air pressure ratio. In this experiment, two types of input; square wave and sine wave are given and the intelligent cylinder is able to follow the target position which validates the function ability of the cylinder with 0.169 mm accuracy.



(a) Experiment result of square wave



(b) Experiment result of sine-wave response

Fig.15 Experiment result of position control

B. Shape Input

Shape input experiment is carried out using Shape input algorithm. The appearance of the experiment is shown in Fig.16. In this experiment, a shape of a virtual 80-faced Polyhedron is constructed with the length data of 120 cylinders in PC. As a result, it is possible to transform various shapes of the virtual 80-faced Polyhedron from deformation of the Active 80-faced Polyhedron. The synchronization of Active 80-faced Polyhedron and virtual 80-faced Polyhedron is confirmed.

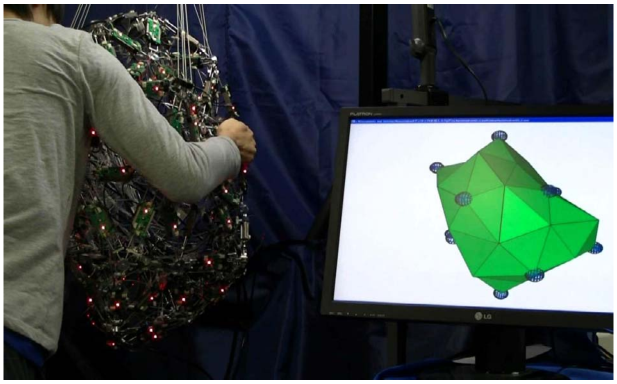


Fig.16 Shape Input experiment

C. Spring motion

Spring motion experiment is performed to evaluate the elastic force of Active 80-faced Polyhedron when the stiffness coefficient is changed. Fig.17 shows two examples of the structure with different elastic force. As a result, this interface can express various elastic bodies and the operator can feel the elastic force when the coefficient parameter is changed.

(a) High elasticity (b) Low elasticity

Fig.17 Spring motion concept

V. CONCLUSION

A new Active 80-faced Polyhedron has been developed using compact intelligent pneumatic cylinder. The intelligent cylinder which has local communication function and position detection simplifies the control and communication system. Two types of spherical joint have been developed to connect the cylinders to form the overall Active 80-faced Polyhedron structure. Communication control system for controlling Active 80-faced Polyhedron achieves response speed of 15 ms and average error rate of 0.0137%.

Three experiments of position control, shape input and spring motion were carried to validate the system. These three experiments realize the physical human and machine interaction.

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