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NEW PNEUMATIC ACTUATORS PRODUCING BREAKTHROUGH IN MECHATRONICS

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ABSTRACT

New pneumatic actuators developed in the author's laboratory will be presented with their applications to new mechatronics. Examples of them are a pneumatic rubber actuator for compliant robots, a micro pneumatic tube actuator assisting the colonscope insertion, a pneumatic stepping motor with high torque and resolution, a pneumatic drive bicycle, an intelligent pneumatic cylinder which has encoder and micro CPU realizing local control and communication functions, and a new control method utilizing multiplex pneumatic transmission for pneumatic systems with multi-degrees of freedom.

KEY WORDS
pneumatic actuator, robot, mechatronics

INTRODUCTION

We have developed many kinds of actuators from nano positioning actuator using piezoelectric material to big force hydraulic actuator and their applications [1, 2]. In this report, our research activities on pneumatic actuators are introduced. They include 1) a small stepping pneumatic motor with high torque, 2) compliant pneumatic rubber actuators, 4) pneumatic drive bicycle, 5) intelligent pneumatic cylinder, and 6) a new control method for pneumatic system consisting of many cylinders.

NUTATION MOTOR

Figure 1 shows an example of the developed nutation motor [3, 4]. It consists of a pair of bevel gears; a cone-shaped bevel gear, shown as a fixed bevel gear in Fig.1 and a cup-shaped bevel gear, shown as a rotary bevel gear, which is supported by a spherical bearing. As the bevel gears have different numbers of tooth, gearing between two gears causes rotation of the rotary bevel gear, resulting in the rotation of the output shaft through the output bevel gears.

The rotary bevel gear is driven by a rubber diaphragm behind it, which has three pneumatic rooms. Driving each pneumatic room sequentially causes the

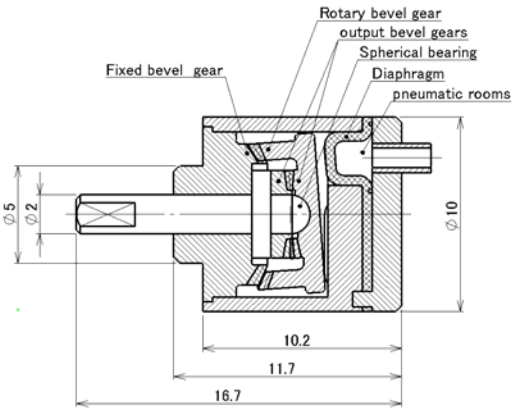


Fig.1 An Example of internal structure of nutation motor

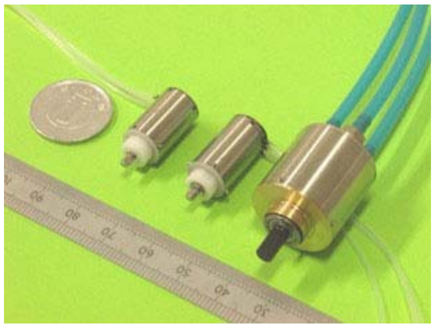


Fig.2 Developed nutation motors

nutation of the rotary bevel gear to drive the motor. As this gear mechanism works as a reduction gear, the motor works as a stepping motor generating big torque.

We have developed many prototypes as shown in Fig.2. The motor shown in Fig.1 has the bevel gears of 30 and 29 in tooth numbers, respectively, and generates the maximum torque of $5.5x10^{-3}$ [Nm] and 4 degree in stepping angle.

COMPLIANT ROBOTS

Manta robot

We developed a bending pneumatic rubber actuator named flexible microactuator, FMA [5] and applied it to various kinds of compliant robots. Figure 3 shows the FMA structure. It is made of rubber and has three internal chambers. Applying air pressure to each chamber causes the motion of three degrees of freedom; bending in any direction and stretching. It is designed based on non-linear FEM, where geometrical and material nonlinearities and contacting problems are analyzed. The analysis results agree well with the experimental results in general as shown in Fig.4 to make us design the actuators easily.

Pneumatic rubber actuators in general are suitable for underwater robots to move smoothly like living creatures because pneumatic rubber actuators have water-resistance, high power density, light weight, and high compliance to deform smoothly with interaction

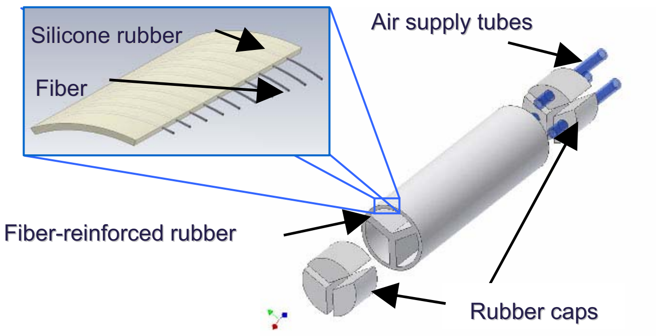


Fig.3 Structure of Flexible Ficroactuator

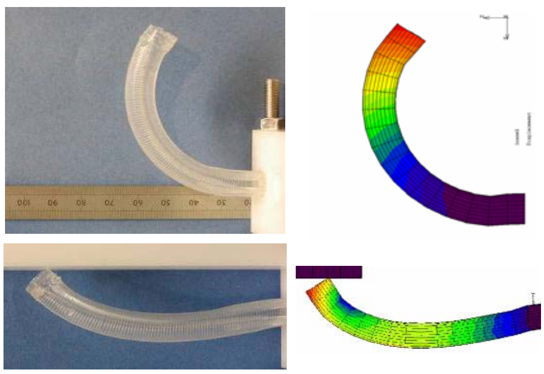


Fig.4 FMA design based on non-linear FEM analysis

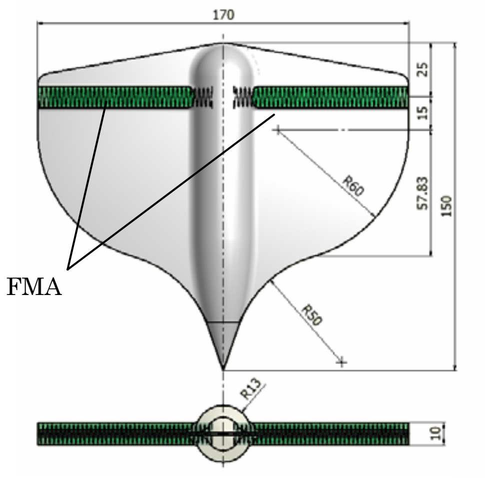
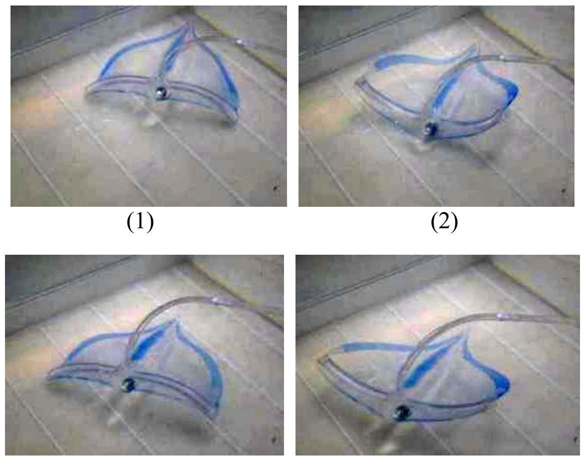


Fig.5 Manta swimming robot



(1) (2)

(3) (4)

Fig.5 Experimental results of manta swimming motions

with water.

A manta type swimming robot is designed as shown in Fig.5 [6]. Two FMAs are embedded in the robot as shown in Fig. 5. The manta robot is 170 mm in width and 150 mm in length. It is made only of silicone rubber. Two flexible pneumatic tubes are connected to each actuator, resulting in four flexible pneumatic tubes in total to drive the robot. The developed manta robot works very well in water with the swimming speed of 100 mm/s and also steers in any desired direction.

Tube actuator assisting colonoscope insertion

Inserting an endoscope into the colon requires very technical procedure and it is difficult in some cases even for experienced doctors. Although active colonoscopes have been researched, these instruments are still in the development stage. Mechanisms for this application are required to be soft enough not to injure the colon wall and being deformable enough to adapt to the curves of the colon. In addition, the mechanisms must generate

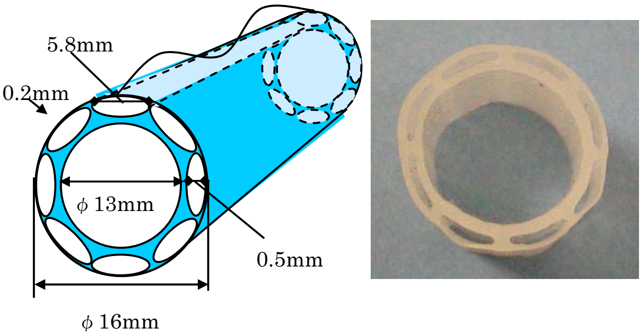


Fig.6 Multi-room rubber tube actuator applied to colonoscope

Fig.7 Simple insertion experiment using a dummy scope with force gauge

distributed force adequate for traveling. These requirements are difficult to be satisfied using conventional mechanisms and actuators. We have designed and developed two types of new driving mechanism using pneumatic rubber actuators and made their feasibility tests [7].

One mechanism is "Multi-room rubber tube actuator", shown in Fig.6: introducing pulse pneumatic flows to a thin rubber tube causes traveling deformation waves on the tube surface, which drives an object placed on the tube. A colonoscope is inserted in the 13 mm hall and applying pulse pneumatic flows generates progressing waves on the tube surface, which convey the colonoscope with the tube itself.

A basic insertion experiment was made using a dummy colonoscope equipped with a force gauge to detect the insertion force of the operator as shown in Fig.7. The path was made of a vinyl hose with the curvature of 17 to 26 cm. Figure 8 shows the force required to insert the dummy scope to the vinyl hose. The upper figure shows the required force without driving the tube while the lower figure shows the required force with driving the tube. Notes such as 60cm and 70 cm in the figure indicate the position of the head of the scope. The horizontal axis indicates

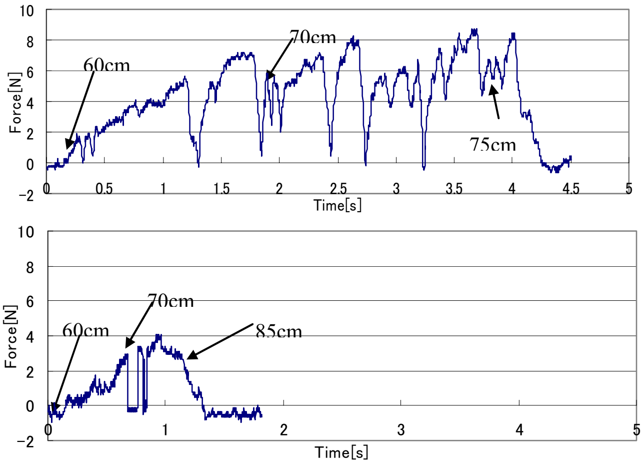


Fig.8 Experimental results of insertion force. The upper figure shows the force without driving the tube and the lower figure shows the force with driving the tube.

time.

As shown in Fig.8, the results show the effectiveness of the thin tube wave generator very clearly; driving the tube enabled the insertion to 85 cm position in 1 sec, while it was difficult to insert the scope beyond 70 cm position without driving the tube because of the friction between the scope and the vinyl hose. It took 4 sec to insert the scope to 70 cm position without driving the tube [7].

The other mechanism is "Tetra Chamber Actuator"[9]: a rubber tube which has four chambers in it is wound around the colonoscope to cause traveling deformation waves on the scope surface by sending pneumatic pressures to each chamber sequentially. Its original idea comes from bubbler actuator [7, 8]. The designed cross section of the actuator and its deformation are shown in Fig.9. It generates the deformation six times larger than that of the conventional bubbler. More information in detail can be found in ref. [9].

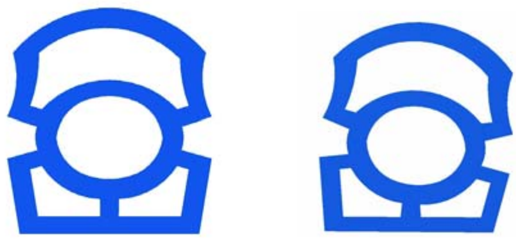


Fig. 9 Deformation of tetra chamber actuator

PNUMATIC BICYCLE

Although pneumatics is not suitable for the transmission of large amounts of power, this technology is suitable for the transmission of smaller amounts of power. By applying pneumatic transmission to bicycles, rather the

Fig.10 Prototype bicycle with pneumatic transmission

conventional chain transmission, two new functions may be realized: 54 gears and energy recovery.

The bicycle shown in Fig.10 has two cylinders connected to the pedals and two cylinders connected to the rear wheel. The cylinders near the pedals generate high pressure air, which is sent to the cylinders near the rear wheel through pneumatic valves to drive the wheel. Switching the valves enables an amazing 54 gears to be realized. During braking, the cylinders connected to the rear wheel work as pumps to generate pressurized air, which is stored in an air tank, enabling energy recovery. The experiments carried out in outside fields showed that that the energy efficiency is about 30% on flat road and the variable-speed function and the energy regeneration function works successfully [10].

INTELLIGENT CYLINDER

A goal of our research is to develop intelligent actuators for small mechatronic systems which have multi-degrees of freedom of motion such as micro robots.

An example of multi-DOF mechatronic systems is shown in Fig.11 [11, 12]. This example is developed for physical human-machine interface which makes the operators feel as if they actually touched

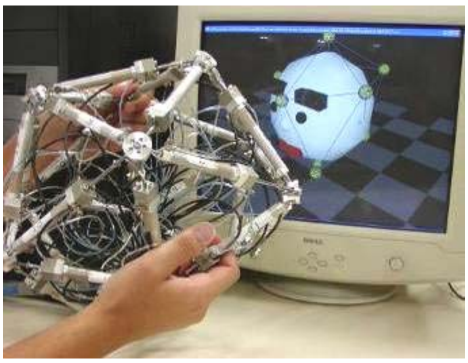


Fig.11 Active polyhedron with 30 cylinders working as a physical human/machine interface

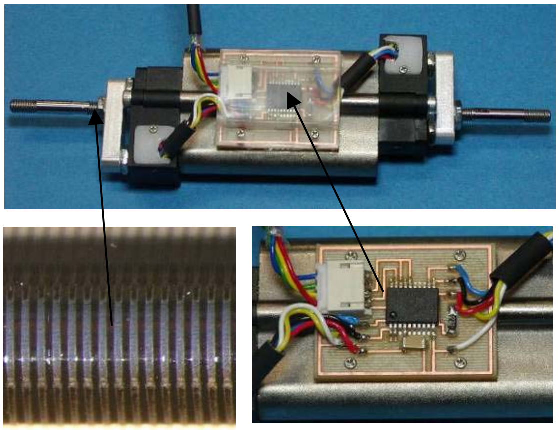


Fig.12 Intelligent pneumatic cylinder, micro CPU, and encoder built in the cylinder

three-dimensional continuous virtual objects in PC. The prototype shown in Fig.11 consists of thirty pneumatic cylinders, forming a linkage mechanism of icosahedron. The final goal of this research is to realize a virtual physical continuous object consisting of a great number of intelligent miniature actuators, and is expected to work as a pre/post processor for analysis of finite elements method.

The development of intelligent actuators is one of the biggest key points to realize these mechatronic systems. The intelligent actuators for these purposes are required to have sensing functions of motions and forces, control function with local signal processing, and communication functions between the other actuators and host computer, which reduces the numbers of electrical/pneumatic cables.

Figure 12 shows an intelligent pneumatic cylinder developed for this pneumatic active polyhedron with 120 degrees of freedom shown in Fig.12. The developed cylinder is almost same sized as conventional cylinder and is equipped with a micro optical encoder to detect position of the piston rod as shown in Fig. 12. In the optical encoder chip a micro LED and two pairs of micro optical lens and photo detector are fabricated. On the surface of the piston rod, 0.16mm stripe marker

Fig.13 Active polyhedron consisting of 120 intelligent cylinders

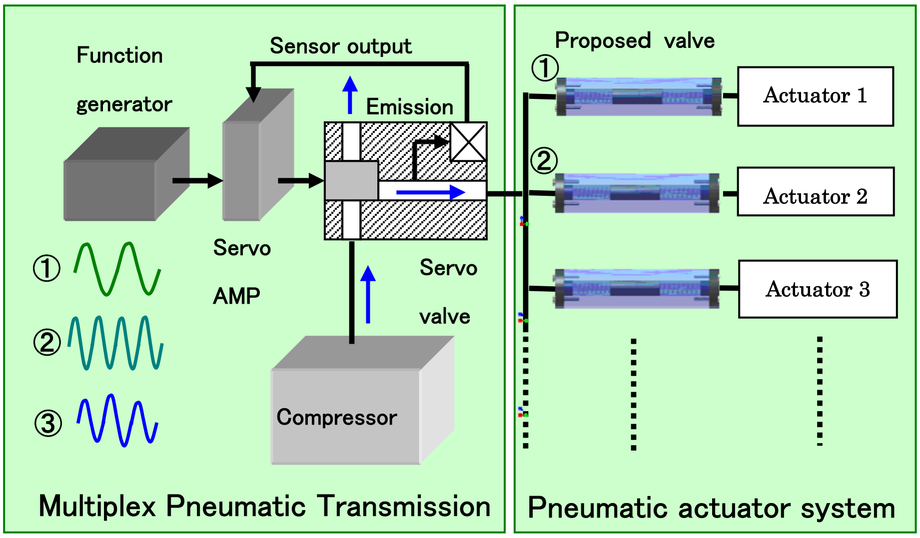


Fig.14 Proposed control system for pneumatic mechanical systems with multi-degree of freedom

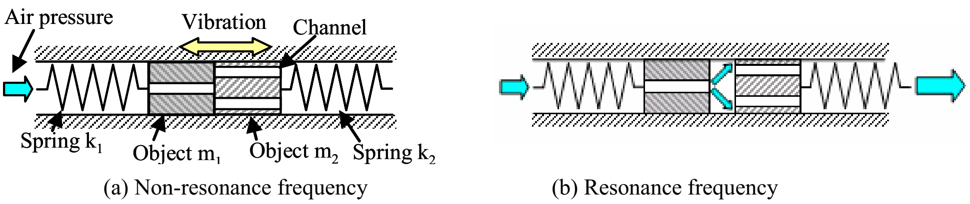


Fig.15 Basic structure of the pneumatic on/off valve which is activated when the pneumatic vibration at the natural frequency is applied to the air supply line

lines are fabricated with oxidization of the stainless steel rod surface by YAG laser marker [12,13].

PNEUMATIC VALVE OPERATED MULTIPLEX PNEUMATIC TRANSMISSION

A new pneumatic valve for controlling pneumatic actuators and its operation system using air vibration in air supply line are newly proposed and being developed [14].

Driving mechanism of this valve and operation system is based on a novel idea: superimposing pneumatic waves into the air supply line drives any selected valve(s) which are connected to the air supply line. Each valve is designed to have different natural frequency to be driven and it is activated when pneumatic vibration at the natural frequency is applied to the air supply line.

Figure 14 shows the outline of pneumatic mechanism to which the proposed control system and the valves are applied. As shown in the figure, an oscillator built in the air supply line gives the supply air vibration.

Each actuator is equipped with the proposed pneumatic valve(s) which has a natural frequency for activation. Superimposing the pneumatic vibrations at the frequency corresponding to the natural frequency of its valve causes mechanical resonance of the oscillating bodies in the valve to drive the actuator.

Since the superimposed pneumatic waves is transmitted in the air supply line as control signals and valve drive energy, electrical cables, which are needed to be connected to each valve in conventional pneumatic drive systems, are not needed in this system. This results in very simple pneumatic systems with multi-degree of freedom.

Figure 15 shows a structure and working principle of the proposed valve. The valve has two oscillating bodies, m_1 and m_2, which have through holes for air flow, and are supported elastically by two springs, k_1 and k_2, respectively. This mechanical system acts as a spring-mass vibration system. Without the pneumatic oscillation at the natural frequency, two bodies contact by the spring force and there is no air flow through the valve, while applying air oscillation of the natural frequency causes the bodies oscillate separately to cause air flow through the valve.

At current, we successfully control two cylinders independently using this system [15]. We are now trying to increase the number of the controlled cylinders.

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