Development of a tactile sensing flexible actuator

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Abstract: In this paper the disadvantages of flexible artificial fingers have been improved. The finger is provided with the tactile sense by two types of sensors to detect the finger tip touches an object and to estimate both the finger force and object size. The rigidity is enhanced by equipping the finger with a reinforcing material similar to that of human's bone. A prototype robot hand with four fingers has been manufactured for experiments and mounted on an industrial articulated robot. The effectiveness of the improved robot hand finger was confirmed throughout experimental tests of grasping action.

1.Introduction

Various types of robots have been studied and developed until now[1]-[3] to replace human handling works by automated manipulators in factories or under the extreme environments such as space, oceans and nuclear power plants[4]. However, the object handlings by these robots were realized by using only the degrees of freedom of the joint mechanisms of arms and wrists; hence, they are naturally lack of flexibility. It is therefore needed to afford the flexible function as human hands to rigid manipulators.

In our laboratory, a flexible artificial muscle actuator made of silicone rubber tube and activated by fluid pressure has been developed[5][6]. The characteristic points of this actuator are (1) simple structure, (2) easy to miniaturize, and (3) capable of movements of higher degree of freedom. However, in comparison to human hands the deficiencies of the hand actuator constituted by four fingers of the artificial muscles were as follows: (4) It has no function of tactile sensing. (5) It lacks of torsional rigidity because it is flexible and has no bones inside its body; thereby leading to the fact that the actuator is twisted when it grasps an object body and is liable to deviate to a direction tangential to the body's surface and normal to finger direction of motion.

In this paper these disadvantages of the artificial finger have been improved. The finger is provided with the tactile sense and the torsional rigidity. A prototype robot hand with four fingers has been manufactured for experiments and mounted on an industrial articulated robot. The effectiveness of the improved robot hand fingers is confirmed throughout the experimental tests of grasping action.

2. Configuration and characteristics of the actuator

2.1 Structure of the actuator developed in the previous report

Figure 1 shows the structure of the artificial finger[5] developed in our laboratory. The actuator is called normal type actuator in this paper. The term of the actuator is used similarly to the meaning of the artificial finger. Namely, the former term is used when it is explained as the machine part and the latter term is employed when it is used as the robot hand finger.

One end of the tube is closed by the plug. In order to reinforce the tube, two types of S- and Z-twisted fibers of about 1/100 dimension as large as the tube diameter are wound densely around the tube and are pasted by the adhesive of the material identical to the tube. These are called the circumferential fibers, which work for preventing the expansion of the tube and for elongating the tube towards only the longitudinal direction when the compressed air is introduced from the open tube end. The reason for the use of dual fiber structure is to prevent even the slight twist which is liable to be caused when the tube is bended. Another reinforcing fiber, called the longitudinal fiber, is pasted on the tube surface along its longitudinal axis. This fiber prevents the tube elongation

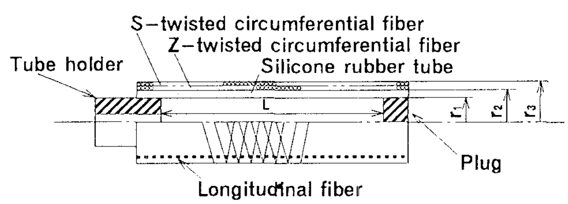


Fig.1 Structure of normal flexible actuator

at the fiber location and works not only for bending the tube along the fiber axis but also for rotating the tube around the axis. By arranging the longitudinal fiber appropriately the tube can be deformed arbitrarily in multi-degrees of freedom[5]. The greatest feature lies, therefore, in the employment of simple structure and the driving mechanism. In Fig.1, the longitudinal fiber is pasted parallel to the tube axis, and it is deformed into an arc shape by pressure application. In this paper the size of the fingers is chosen as L=80mm, r_1 =5mm, r_2 =6mm, and r_3 =7mm.

2.2 Structure of improved actuators

When the above actuator is used as the robot hand fingers for grasping object bodies, the actuator is twisted and deviated to a direction tangential to the body's surface and normal to finger direction of motion because of the lack of its rigidity. To solve this problem, two types of fingers are manufactured for experiments and their mechanical characteristics are compared; namely, (a) the one where a longitudinal cloth is pasted in the axial direction and (b) the other one in which a reinforcing material is installed.

Figure 2 shows the structure of the finger reinforced by a cloth of 0.3mm thick which is pasted on the half tube surface like the human's skin. The aim is to increase the finger's rigidity by enlarging the part of the tube surface area which is difficult to be deformed with the use of the cloth.

Figure 3 shows the structure of the finger in which the reinforcing material is installed. This finger is reinforced by the longitudinal fiber similar to the original one. Moreover, the reinforcing plate is installed in the center axis of the tube. The material suitable for this reinforcing plate is as follows: i) it has the degree of flexibility such that it does not give the appreciable effect on the finger bend in the downward direction of the paper in Fig.3 and ii) it has also the rigidity to some extent in the direction normal to the deformation (normal to the paper). Considering these characteristics a plastic plate was employed as the reinforcing material. The size of the plate installed in the finger is 10 mm width by 1 mm thickness. The left end of the plate is fixed at the tube holder and the right end is set free such that it can slide in a guiding groove shaved in the end plug. The reason why we employed this structure is that the finger is able to be bent by pressurizing the tube in spite of the increase in rigidity of the reinforcing plate. If both ends of the plate are fixed, not only the plate but also the rubber tube would not be bent by the ordinary pressure application.

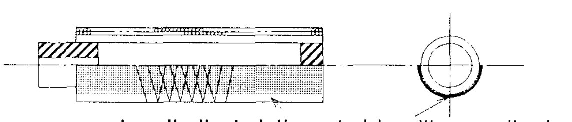


Fig.2 Structure of flexible actuator with longitudinal cloth

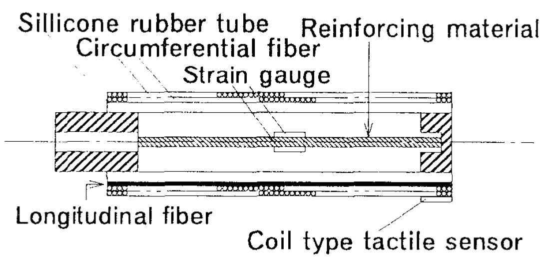


Fig.3 Structure of artificial finger with reinforcing plate and tactile sensors

2.3 Characteristics of the actuators

2.3.1 Pressure application system

Figure 4 shows the pressure application system. The compressed air from a compressor is regulated at a necessary pressure by a servo valve unit and is fed to an artificial finger. This servo valve unit is the device controlling precisely the air pressure according as the input electric current. The servo drive unit generates control electric current according as the numerical command values from the host personal computer and feeds the electric current to the servo valve unit. The air pressure is monitored by a digital pressure gauge situated between the valve unit and the flexible actuator. The pressure controlling range is about 0.05 to 0.5 MPa gage.

2.3.2 Pressure and bend angle

The relationship between the pressure applied to the artificial finger and the bend angle θ was examined. The bend angle θ is defined as the angle difference between the original finger axis and the bend direction of the finger tip.

Figure 5 compares the bend angles respective of the fingers with a longitudinal fiber (normal type actuator),

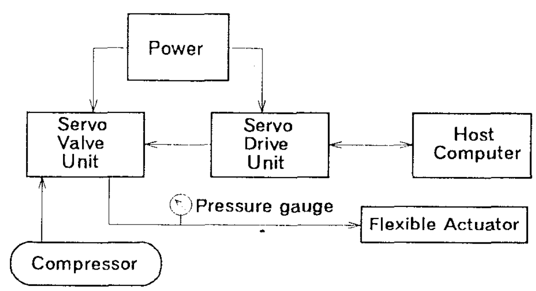
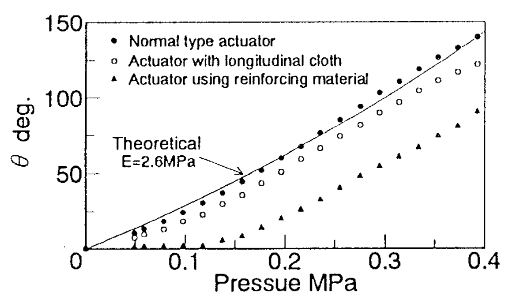


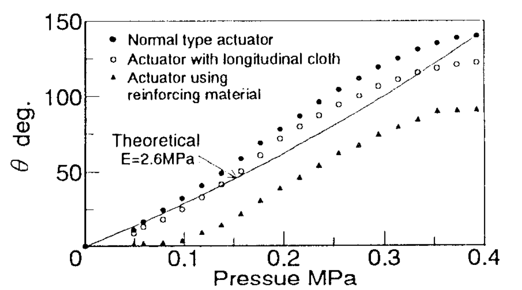
Fig.4 Construction of the system

with a longitudinal cloth and with a reinforcing plate. Figure 5(a) compares the results when the pressure is increased, whereas Fig.5(b) shows the data when the pressure is decreased. The solid lines in both figures represent the theoretical results for the normal type actuator. The explanation of the analyzing method[5] is abbreviated here because of the page consuming analysis, however it is seen that the theory expresses well the deformation process of the normal type actuator in the pressure increasing process. The difference between the bend angles in the pressure increase and decrease means the presence of the hysteresis characteristics. Since the hysteresis was small in the single circumferential fiber, it is considered to be due to the use of the double wounded circumferential fibers. The hysteresis of this magnitude doesn't cause severe inconvenience in the finger motion and is allowable for the use as robot hand fingers.

In the finger with the reinforcing plate, the bend angle is small compared to the other two. Furthermore, as a noteworthy result, the insensible range is seen. This is due to the fact that the plate tip slides in the groove in the initial deformation range of the finger. In each case of increasing and decreasing pressure it is seen that the pressure addition as high as about 0.1 MPa is needed to get the same bend angle as the other two. The need of the pressure addition is somewhat disadvantage. However, the pressure increase such as this order doesn't induce any particular problem in the performance of the air compressor used.



(a) change of the bend angle with increasing pressure



(b) change of the bend angle with decreasing pressure

Fig.5 Relationship between the pressure and the bend angle

2.3.3 Strength of the finger against the force normal to the direction of the finger deformation

In order to examine whether the fingers can hold safely the object body or not, the strength of the fingers against the force normal to the direction of the finger deformation is an important evaluation standard as well as the grasping force. This is because the weight of the object body always works on the fingers in the direction normal to the finger axis when the artificial hand holds the body horizontally. Hence, the relationship between the bend angle as an index of the grasping force and the lateral finger rigidity normal to the finger deformation was examined.

Figure 6 shows the measuring method of lateral rigidity. The finger is bent with increasing the applied pressure slowly to the desired bend angle and the force gauge is pushed 10 mm down at the finger tip in the direction normal to the bend direction, then the force of which the finger tip pushes back the force gauge is recorded as the lateral rigidity.

Figure 7 compares the variations of the finger rigidities against bend angles. It is found that the normal type actuator has very small lateral rigidity and that the usage of the plate serves appreciable regidity increase, whereas the usage of the cloth serves only a little rigidity increase. The rigidity increase becomes smaller with the increase of the bend angle because the lateral distance from the original finger axis to the finger tip, or, to say in

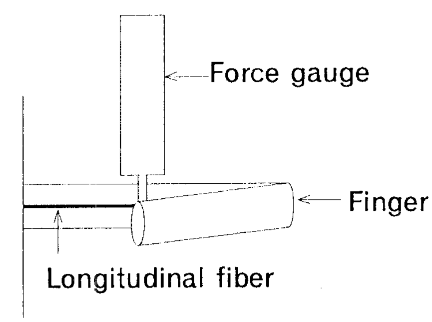


Fig.6 Method to measure the lateral rigidity of the finger at the pressurized state

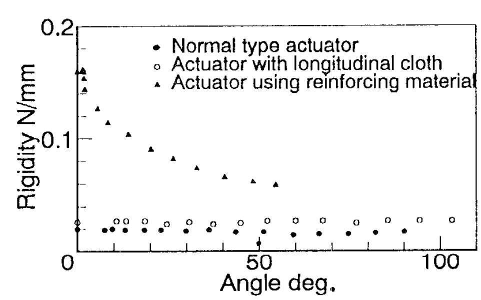


Fig.7 Relationship between bend angle and lateral rigidity

other word, the moment applied to the finger becomes greater. This result means that the finger with the reinforcing plate can be a practical one. It is expected that the finger with the reinforcing plate is preferable for grasping and that the problem of the finger torsion can be appreciably reduced; therefore, this type of finger is hereafter used in this paper.

3. Installation of tactile sensors

3.1 Coil-type tactile sensor

Figure 8 shows the structure of the coil-type tactile sensor pasted on the finger tip surface in Fig.3. This sensor is composed of a conductive rubber sheet and two electrodes of coiled copper wire pasted on both surfaces of the rubber sheet just like the human fingerprints. Since the employment of normal adhesive will increase the electric resistance up to the value of nearly non-conductive material, attention is paid on reducing the resistance by mixing the adhesive with conductive whiskers. As the resistance of the conductive rubber varies from the insulation state to the well conductive state lower than 50 Ω, it is possible by using this relationship to detect the force applied to the tactile sensor as a voltage change.

Figure 9 shows the relationship between the force applied on the sensor surface and the output voltage. In the measuring circuit the resistance of 5M Ω was connected in series to the sensor. The voltage of 5 V was applied to the circuit and the junction point voltage was read under the state of force application. From the figure it is convinced that only small force causes significant output change and there is the hysteresis-like difference

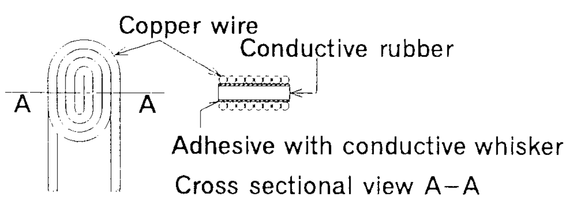


Fig.8 Structure of tactile sensor using conductive rubber

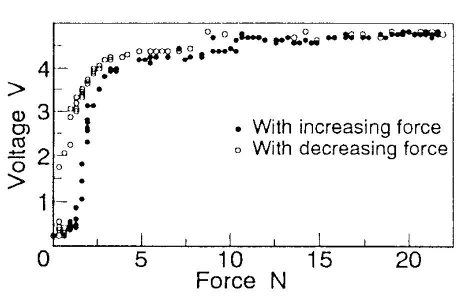


Fig.9 Variations of the sensor outputs against the forces

in variations between the states in increasing and decreasing the force. It is therefore concluded that the judgment of the exact force under small force application is difficult but this sensor can be used as a touch sensor because the output voltage varies like the fashion of the digital change according as the force application.

3.2 Tactile sensor using strain gauge

Since the reinforcing plate is also bent according as the arc-type bend of the finger, if strain gauges are pasted on the surface of the plate, it is considered that they can carry out the function of the tactile sensor. According to this idea, semi-conductive strain gauges are pasted on the both sides of the plate at the midpoint of its length and the relationship between the strain gauge output and the force loaded on the finger tip was measured.

Figure 10 shows the outputs of the strain gauge Wheastone bridge when there is no force application but the pressure inside the finger is increased and decreased. The linear relationship is found between the pressure and the strain gauge output in both pressure increase and decrease cases if the pressure is larger than 0.1 MPa. In this range of pressure, the hysteresis is low enough. Under this pressure relatively large hysteresis is seen which is caused by the slide in the groove of the right hand side end of the reinforcing plate.

Next, the relationship was measured between the force applied to the finger tip and the decrease in the strain gauge output when the pressure is kept constant. Figure 11 shows the relationships taking the pressures as parameters. Two types of linear relationships corresponding to the pressure ranges over and lower than 0.098MPa can be seen in the figure, which are regarded respectively as the cases without and with the influence of the slide of the plate at the initial deformation stage.

The results obtained in Figs.10 and 11 indicate that the unknown force loaded at the finger tip can be estimated since the pressure is judged by the control signal. However, only the linear relationship when the pressure is larger than 0.1MPa is hereafter used in the

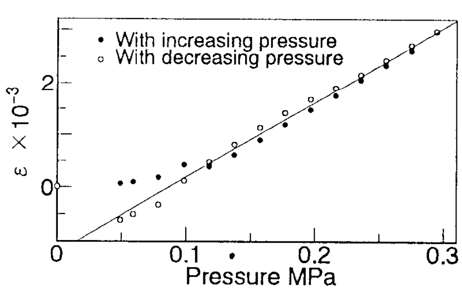


Fig.10 Relationship between the pressure and the strain at the midpoint length of the reinforcing plate

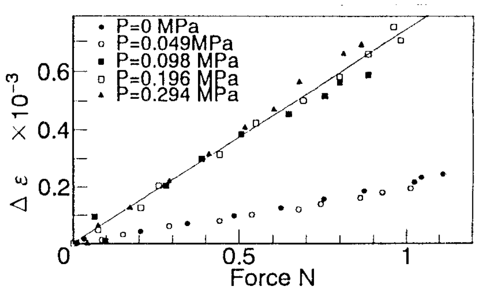


Fig.11 Relationships between the force addition and the strain decrease

measurement because another relationship lacks somewhat reproducibility.

4. Experiment of grasping bodies

Figure 12 shows the articulated robot hand system used in the experiment of grasping bodies. This system is composed of a robot arm unit, a hand unit and a sensor unit. Figure 13 shows the appearance of the hand unit with four artificial fingers, where the angle between the opposing fingers is 60° at the zero pressure state and the distance between their tips is 11cm. When the pressure is applied the four fingers are bent simultaneously and their tips touch each other at the pressure application of 0.25MPa. The procedure of grasping the object is as follows: Firstly, the arm and hand unit are moved near to the object. Next, the hand unit grasps the object through the arc-like deformation of the fingers by the pressure

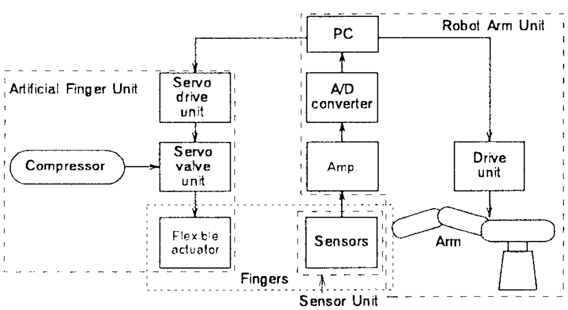


Fig.12 Construction of robot arm and hand

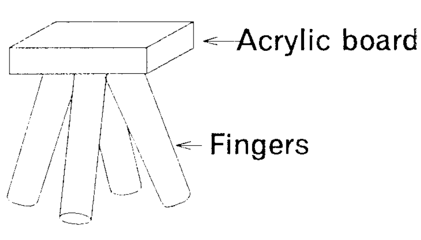


Fig.13 Appearance of the robot hand

application. Then, the object is picked up and moved to the prescribed location and is set down there by decreasing the pressure.

Using this system experimental tests have been carried out whether or not this system can detect the time when the fingers touch an object body and estimate its outer diameter of the body, and can estimate the grasping force.

4.1 Judgment of the touching time to the object

Figure 14 illustrates the relationship between the output voltage of the tactile sensor and the pressure when the hand fingers hold a ball or an egg. In the figure the pressure when the hand fingers touch the object is shown by arrows, and it is found that there is a slight voltage increase at the instant of touch. Although output signal at this instance was low, it was easy to detect. Thereafter, the output voltage increases with increasing further the pressure but the output cannot be used as the holding force because the angle when the sensor touches the object becomes the different one according as the change of the finger bend angle. However this is not the problem since the sensor is used only for detecting the touch instant.

4.2 Estimation of the grasping force

Figure 15 shows the relationship between the applied pressure and the strain change when the hand grasps one of three kinds of objects. The experimental plots of solid circles mean the data for the free change of finger,

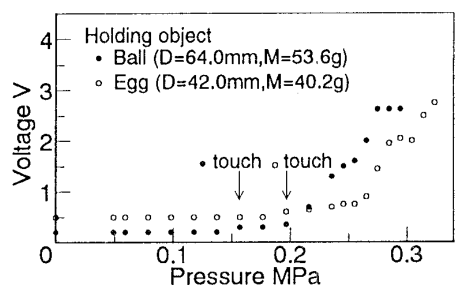


Fig.14 Variations of the sensor outputs when the finger touches different objects

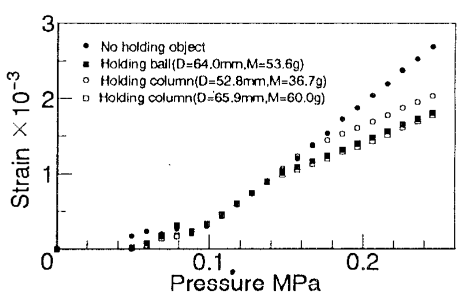


Fig.15 Variation of the strain gauge outputs when the fingers grasp different size objects

namely, in the case that the finger and the reinforcing plate are bent but the hand fingers grasp nothing. The other three kinds of plots mean the cases that the fingers grasped different object bodies at the gradiant change points of pressure increase curve. In the pressure range over the points, the increasing rates reduce because the grasping action decreases the bend angle of both the finger and the reinforcing plate. It is also seen that the pressure at the change point becomes lower with the increase of the diameter of the grasped body.

As stated in Figs.10 and 11, the force applied to the finger tip can be estimated by reading the difference between the data of free finger(solid circles) and the data of the finger grasping a body. From this fact the force acted at the finger tip was computed and the relationship between this force and the pressure was arranged in Fig.16. In this figure it is clearly shown that before the finger touches some object body the force remains nearly zero but after the finger touches the object body it increases linearly with the increase of pressure and the increasing rates of the force with the pressure increase are almost the same to each other independent to the grasped bodies. From this result it is concluded that the grasping force can be estimated easily in this hand finger system.

4.3 Estimation of the outer radius of the object body

Figure 17 shows the relationship between the finger tip distance and the pressure, where the dashed line is the limit distance between the fingers. Since the straight finger is bent into the arc-shape such that the finger

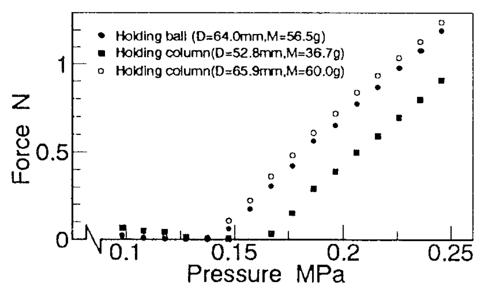


Fig.16 Estimation of the grasping force

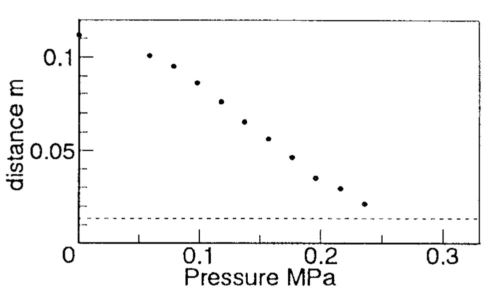


Fig.17 Variation of the finger tip distance with the increase of pressure

curvature is reciprocally proportional to the pressure, the finger tip distance decreases monotonously with the increase of pressure. Using the relationship measured preliminary, we can estimate the object size easily. For instance, the pressure when the finger touches the ball in Fig.14 is about 0.155 MPa, and it is estimated from the relationship in Fig.17 that the finger tip distance (ball diameter) is about 65mm. The pressure when they grasp an egg is about 0.19 MPa and the finger tip distance (egg diameter at the grasping point) is similarly estimated as about 40mm. Thus, it is concluded that the present hand finger system with the use of the tactile sensors can easily judge the object body size.

5. Conclusions

Summarizing the obtained results, the following conclusions were drawn.

(1) The lateral rigidity is improved by inserting a reinforcing plate in the finger without losing the merits of flexibility in the motion of finger.

(2) By equipping the finger with two types of developed tactile sensors, it became possible to detect the instant when the finger tip touches an object and also to estimate the force of grasping the object.

(3) The robot hand with four fingers equipped with the tactile sensors can judge roughly the size of the grasped body.

(4) It is expected that the feedback control with the combinational use of the tactile sensors and the hand finger system will realize a new type of intelligent hand system.

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