Pneumatic Soft Actuator using Twist of Flexible H-Structure

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ABSTRACT

A new pneumatic soft actuator has been developed. The actuator is made of silicon rubber tubes, which is constructed in the H-structure. The actuator has three degrees of freedom, expanding in the vertical direction, bending in the horizontal direction and rotating around the vertical centerline of the H-structure, each motion can be obtained by adjusting the inner pressure of three silicon tube segments constructing the H-structure. This paper describes the principle of the actuator and some experimental results and discussion. The results shows the availability of the proposed actuator.

KEY WORDS

Pneumatic actuator, Soft actuator, Silicon rubber, Pressure control, Human friendly robotics,

INTRODUCTION

A human friendly robotics and mechatronics have attracted interest recently, which require a flexible mechanism. In order to assure the safety for human, such mechanism should be driven with an inherently soft actuator. The soft actuator has to be provided with both the flexibility for the environmental objects and the satisfactory controllability to attain the desired operation. A pneumatic actuation can become one of the most effective ways to satisfy the above requirements. A combination of pneumatic actuator with a proper control strategy is most available to realize the soft actuation system [1],[2].

In this study, a new pneumatic soft actuator has been developed. The newly developed actuator is made of silicon rubber tubes, which are constructed in the H-structure. The actuator has three degrees of freedom, expanding in the vertical direction, bending in the horizontal direction and rotating around the vertical centerline of the H-structure, each mo-

tion can be obtained by adjusting the inner pressure of three silicon tube segments constructing the H-structure.

By coupling some H-structure, an actuator with multi-degrees of freedom can be built up. Also some kinds of constructions of this actuator unit can be considered.

This paper describes the operational principle and the fundamental characteristics of this actuator unit.

STRUCTURE OF ACTUATOR

Figure 1 shows the principal structure of the actuator. It constructs a H-structure with three silicon rubber tubes 1, 2 and 3. A tube 4 is an auxiliary one to deliver the output from the actuator. The tubes are bonded each other, but there is no air flow between each tube. The inner pressures in tubes from 1 to 3 are adjusted to make a desired configuration of the H-structure.

The tubes are reinforced with fibers as shown in Figure 2. Tube 1 and 2 are reinforced in the radial

Figure 1: Structure of actuator

direction, so that, pressurizing these tubes, which stretch in the longitudinal direction rather than the radial direction. When reducing the pressure, the tubes return to the original length due to the own elasticity.

Figure 2: Reinforced tubes

The tube 3 is wrapped with a fiber around the circumference and in the longitudinal direction with an inclination angle of α . Pressurizing the tube 3, it is twisted in the direction for the angle α to become zero. The maximum twist angle θ_{max} depends on the tube size and the inclination angle, given by Eq.(1) as shown in Figure 3(a).

$$\theta_{max} = L_2 \tan \alpha / \pi d_1 \times 360 \quad (1)$$

Where it is assumed that the fiber does not expand and contract. L_2 , d_1 and α are tube length, outer diameter of tube and inclination angle of fiber, respectively, in the initial condition. The tube length L' at the maximum twist angle is given by

$$L' = L_2 / \cos \alpha \quad (2)$$

Also, as shown in Figure 3(b). The relation between the changes of twist angle and tube length can

be expressed by

$$\Delta\theta = \frac{L_2 \tan \alpha - L_2 \tan \alpha'}{\pi d_1} \times 360 \quad (3)$$

$$\alpha' = \cos^{-1} \frac{L_2 + \Delta L}{L'} \quad (4)$$

$\Delta\theta$ and ΔL denote the respective changes.

(a) Maximum twist angle

(b) Change of twist angle

Figure 3: Twist motion of tube 3

Figure 4(a) shows θ_{max} calculated from Eq.(1). Figure 4(b) shows the relation between $\Delta\theta$ and ΔL calculated from Eqs.(2),(3) and (4) for some values of α . Where the initial tube length L_2 is assumed to be 60[mm], and the outer diameter of tube d_1 is 10[mm].

The large α increases θ_{max} , but also the ratio of $\Delta L / \Delta\theta$ becomes large. It is not desired for the tube 3 to largely expand in the actuator of H-structure when it twists. Therefore the value of inclination angle α should be as small as possible in the region where the desired θ_{max} can be obtained.

PRINCIPLE OF ACTUATOR

Figure 5 shows the fundamental three motions of the actuator, where the bottoms of the tube 1 and 2 are assumed to be fixed.

(a) Calculated maximum twist angle

(b) Calculated relation between $\Delta\theta$ and ΔL

Figure 4: Fundamental property of tube 3

Figure 5(a) shows the expansion and contraction motion in the direction of z axis. By uniformly increasing the pressures P_1 and P_2 , respectively in the tube 1 and 2, that is, $P_1 = P_2$, the actuator expands, and by reducing them it contracts due to the elasticity of a silicon rubber. Figure 5(b) shows the bending motion in the y direction. By adjusting $P_1 > P_2$, the actuator can bend to the direction of positive y axis owing to the difference of the length of two tubes. When $P_1 < P_2$, it can bend to the negative one. Figure 5(c) shows the twist motion around the z axis, which is caused by pressuring the tube 3.

As mentioned above, by adjusting P_1 , P_2 and P_3 the actuator can attain the three degrees of freedom motion, of which the variable displacements are x_L , ψ and θ_2 .

EXPERIMENTAL SETUP

Figure 6 shows the experimental setup. A silicon rubber tube with outer diameter of 10[mm] and wall thickness of 2[mm] is used. The tube segments are bonded each other by the silicon rubber adhesive. Photograph 1 shows an experimental actuator. The compressed air is supplied to each tube through a plastic connector from a pneumatic servo control valve. The inner pressures P_1 , P_2 and P_3 are adjusted by the feedback controller using a personal

Figure 5: Fundamental three motions of actuator

computer. The variable displacements x_L , ψ and θ_2 are measured with a visual motion analyzer.

Figure 6: Experimental setup

EXPERIMENTAL RESULTS AND DISCUSSION

An experimental actuator is composed of the tubes 1 and 2 with length of 100[mm], outer diameter of 10[mm] and wall thickness of 1[mm], which are wrapped with a fiber every distance of 5[mm]. The tube 3 has the length of 60[mm], the same diameter and thickness as tubes 1 and 2, which is wrapped at every distance of 15[mm] in the circumferential direction

Photograph 1: Experimental actuator

and with the inclination angle α of 20[deg] in the longitudinal direction.

FUNDAMENTAL CHARACTERISTICS OF TUBES

Figure 7(a) shows the expanding displacements of tube 1 and 2 for the inner pressure. A symbol of $\bullet$ denotes the average value, a symbol of vertical segment denotes the amount of scatter of measured values. For example, when the inner pressure $P=200\text{kPa}$, the tube 1 and 2 can expand by about 18%.

The measured twist angle θ_1 of the tube 3 is shown in Figure 7(b) for some values of inner pressure. When $P=200\text{kPa}$, the tube can twist about 150[deg]. These longitudinal displacement and twist angle are expected to be sufficient to drive the H-structure actuator.

FUNDAMENTAL PERFORMANCE OF ACTUATOR

A H-structure actuator is constructed by using tube 1,2,3 and 4. The tube 3 and 4 are bonded at a height of 50[mm] and the top of tubes 2 and 3, respectively. The tube 4 is not pressurized, of which inner pressure is always atmospheric. The tube 1 and 2 build at a distance of 70[mm] between central axes each other.

Figure 8(a) shows the expanding displacement x_L of the actuator for some inner pressures ($P_1 = P_2$), which are measured at the center of the tube 4. The expanding displacement is made a little smaller compared with the values for single tube shown in Figure 7(a). The bonding parts between tube 1, 2 and 3 may cause this decrement.

(a) Expanding displacements of tube 1 and 2

(b) Twist angle of tube 3

Figure 7: Fundamental characteristics of tubes

(a) Expanding displacement

(b) Bending angle

(c) Twist angle

Figure 8: Fundamental performance of actuator

Figure 8(b) shows the bending angle ψ to the direction of the y axis at increasing P_1 when $P_2 = 0$. Figure 8(c) shows the twist angle around the z axis when only the tube 3 is pressurized, the other tubes are in the atmospheric pressure. There is a little hysteresis, but, since it is almost included in the range of the scatter, it is not illustrated in the figures.

The results shown in Figure 8 can prove the availability of the proposed actuator.

MULTIPLE OPERATION

Two degrees of freedom in the actuator are simultaneously driven to show the possibility of the multiple operation of the proposed actuator.

Figure 9 shows the combination of the displacement in the z axis and the bending to the y axis. It shows x_L and ψ , respectively, measured at increasing the pressure P_1 in tube 1 for some values of the pressure P_2 in tube 2 shown in figures and $P_3 = 0$. ψ can be controlled by adjusting the pressure difference $P_1 - P_2$. Since the tube 4 is displaced by bending, x_L changes due to P_2 .

Figure 9: Combination of displacement x_L and bending angle ψ ($P_3=0$)

Figure 10 shows the combination of the displacement x_L in the z axis and the twist angle θ_2 around the z axis. Such multiple operation can be realized

by pressurizing both tube 1 and 2 at the same values and the pressure P_3 in tube 3 at some values shown in figures. When θ_2 increases, x_L is made decreased because the tube 1 and 2 are bent in the opposite directions each other by their twisting as shown in Figure 5.

Figure 10: Combination of displacement x_L and twist angle θ_2

Figure 11 shows the combination of θ_2 and ψ , which can be realized by pressurizing P_1 and P_3 , when $P_2 = 0$. Both angles are shown in figures in which the values of P_3 are shown. Ideally ψ is desired not to be influenced by the pressure P_3 , however, it depends on also P_3 .

The results can prove the possibility of multiple operation of the proposed actuator. However, a certain operational interaction exists due to the structure of actuator.

CONCLUSION

A pneumatic soft actuator made of silicon rubber tubes has been developed, which is based on a H-structure and can operate with a three-degrees of freedom. This paper describes the principle of the actuator and some experimental results and discussion. The results have shown the availability of the

Figure 11: Combination of twist angle θ_2 and bending angle ψ ($P_2=0$)

proposed actuator. Although a certain structural interaction among operational axes, the interaction will be decoupled by introducing a feedback control strategy.

This kind of soft actuator can be applied to various driving mechanism. We are now considering its application.

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REFERENCES

1. Noritsugu, T., Pneumatic Actuators, Journal of the Robotic Society of Japan, 1997, 15-3, pp.355-359.
2. Noritsugu, T., Human-Friendly Soft Actuator, International Journal of the Japan Society for Precision Engineering, 1997, 31-2, pp.92-96.