Fabrication, Mechanical Modeling, and Experiments of a 3D-Motion Soft Actuator for Flexible Sensing

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ABSTRACT

This paper introduces the modular design and manufacturing method, mechanical model, and test verification of a new type of soft actuator driven by fluid. First, the modular design scheme and driving principle of omnidirectional bending and elongation of the soft actuator are described. Three print-based elastic air cavities constrained by fire lines are distributed radially inside the actuator. The actuator can complete the 3 DOF motions of omnidirectional bending and elongation. From the basic principle of material mechanics, a novel mechanical model of the soft elastomer actuator is established. By numerically solving the nonlinear model, the relationship between actuator elongation/bending angle and driving pressure is obtained. The theoretical prediction and test results show that the deformation of the actuator exhibits a linear relationship with pressure when the chambers are charged. Additionally, the maximum allowable load force on the actuator terminal also exhibits good linearity when the driving pressure increases. Furthermore, the established mechanical model, which considers gravity effects can more accurately describe the features of bend and elongation of the actuator. The results show that the proposed model is more convenient than the FEM models. This study provides theoretical support for accurate control of a soft actuator.

INDEX TERMS

Enter soft actuator, multiple degrees of freedom, omnidirectional bending, mechanical modeling, experiment, flexible sensing.

I. INTRODUCTION

With the continuous development of human society, new materials, sensing technique, and automatic control theory, robots have become an important research topic worldwide [1]. Traditional rigid robots are primarily made of rigid materials with limited elastic deformation ability. Their shapes adapt to specific external constraints and obstacles, and they exhibit motions with high accuracy. However, in different circumstances, it is difficult for them to exhibit high deformability and adaptability [2]. Particularly, in special fields such as medical care and complex terrain exploration, more stringent requirements are imposed on robots. Soft robots that can adapt to unstructured environments have become a popular research topic. A soft robot mimics mollusks in nature; it uses soft materials such as silica gel or molded materials and a fluid-driven method. These robots have large deformation, high adaptability, and wide application potentials [3], [4]. Recently, the continuous advancement of new materials, new sensing technologies, 3D printing, micro–nano processing technology, artificial intelligence, and machine learning has further promoted the development of related research on soft robots at home and abroad, in which significant results have been achieved [5]. Meanwhile, the soft actuation technique has also promoted the development of the flexible sensing systems, such as flexible vision system for surgical operations [6], [7].
gripper had seven degrees of freedom and could complete basic grasping actions [8]. Subsequently, with the development of new materials and processing methods, the design concept of soft robots has been continuously improved, and the driving methods diversified. The multi-section continuous flexible robot OctArm series designed by the Walker team at Carnegie Mellon University is powered by a pneumatic artificial muscle. The robot adopts a three-chamber symmetrical structure design with a large deformation range, which can realize elongation and bending motions and exhibits excellent flexibility [9], [10]. In 2014, Daniela et al. of the Massachusetts Institute of Technology (MIT) developed a pneumatically driven soft manipulator to achieve an in-plane bending motion. In addition, a soft gripper was placed at the end of a manipulator, which could realize grasping tasks in a two-dimensional plane. Subsequently, in 2016, MIT developed a 3D soft motion manipulator, which could achieve omnidirectional bending. This manipulator exhibited strong environmental adaptability and could complete movements under special conditions (high temperature, water, and automobile rolling [11], [12]). According to the biological characteristics of an octopus’ tentacles, the EU’s “Octopus Plan” researchers developed a series of imitation octopus tentacles from 2009 to 2015. They adopted an axial line drive unit and radial shape memory alloy drive unit to simulate the longitudinal and transverse muscles of an octopus, respectively. These imitation octopus tentacles could complete the flexible movements of an octopus’ tentacles, which have extremely high bionic value [13]–[15]. In 2016, researchers at Harvard University developed a multi-segment flexible manipulator composed of ionic polymer–metal composite material (IPMC). The manipulator comprised six flexible IPMC arms, each of which could be controlled independently, and the manipulator could perform complex path planning tasks [16]. A high-performance soft bionic robot fish was developed by the Soft Robot Laboratory of Zhejiang University in 2018. Through the response of a high dielectric projectile body membrane to an alternating current voltage, the robot fish transformed the change in membrane tension into a flapping motion to obtain the hydrodynamic force through its flexible fins [17]. Octobot, a soft robot developed by Harvard University in 2016, adopted a microchannel chemical reaction drive, relied on a specific chemical reaction to provide drive energy, and used a microchannel embedded in a soft robot to control energy transmission to realize its driving motion [18]. The pneumatic underwater manipulator and flexible gripper developed by Wen et al. from Beihang University from 2016 to 2018 were composed of two curved segments, an elongated segment, and a flexible gripper, which could realize three-dimensional space movements and perform underwater grasping tasks [19]–[21].

B. KINETIC MODEL AND MOTION CONTROL OF SOFT ROBOT

Unlike the motion of a rigid structure, which can be described by six degrees of freedom, the motion of a soft body is not limited to plane motion. Flexible materials are super elastic and can undergo deformations such as bending, twisting, stretching, and compression. This type of motion can be regarded as an infinite number of degrees of freedom, which complicates the modeling and motion control of soft robots. Soft robots require new modeling and control methods. Because most soft robots are designed based on the principle of bionics, many scholars have used experimental methods to perform the biomechanical analysis and modeling of their bionic objects. For example, Mazzolai et al. [22] dissected an octopus’ tentacles, analyzed its muscle structure, and measured its stress–strain curve experimentally. Additionally, some scholars, such as Yekutieli et al. [23]–[25], have applied theoretical analysis methods to establish a two-dimensional multi-segment lumped parameter dynamics model of octopus tentacles to study motion control strategies. Likewise, a description of the motion of soft robots using a continuous rigid body equation exists. Marchese et al. [26] proposed a simplifying piecewise constant curvature assumption to model the forward and inverse kinematic relationships between an arm’s arc space and a task space. Subsequently, they adopted PID control and visual feedback to realize the path tracking control of “point to point” at the end of a soft manipulator. Wang et al. [27] added curvature and strain vectors to the dynamic modeling of a line-driven soft robot arm based on the Cosserat beam theory and the Kelvin model. Subsequently, a FPG sensor network was utilized to detect the shape of the manipulator, and the adaptive control system of the manipulator was established based on visual feedback [28]. De Payrebrune and O’Reilly [29], [30] established a nonlinear rod model based on Euler’s elasticity theory to analyze the movement of a pneumatic soft manipulator and accurately captured the constitutive relation of its deformation. Subsequently, a five-parameter constitutive relation was established through a nonlinear rod model and the effect of this constitutive relation on the flexible manipulator was studied using the finite element model [31].

Soft robots offer more advantages compared with rigid robots for flexible sensing owing to their good environmental adaptability and shape control flexibility. However, the development of soft robots involves bionics, soft materials science, and robotics. Currently, many challenges exist in the fields of flexible materials, robot modeling and simulation, and sensing and control. A soft robot has a high degree of freedom, which is distinct from traditional robots in terms of modeling and control. The existing dynamic modeling method cannot easily and accurately describe the motion characteristics of a robot. Furthermore, the existing model is complex, which complicates the subsequent motion control. The development of control strategies and modeling methods suitable for soft robots with large deformation and a high-degree of freedom is critical to their practical application.

This paper first introduces the design and manufacturing of a new type of soft elastomer actuator, which exhibits the following unique features: The soft actuator has three elastic air chambers constrained by double spiral windings in the
radial direction, which allows 3 DOFs in omnidirectional bending, elongation. Subsequently, the mechanical model of the soft actuator is established. Compared with other existing models, the model can accurately describe the bending and elongation motion of the actuator. It is simple in structure and can be conveniently used in control strategies. Finally, bending and elongation tests were performed on the designed under a specified pressure, and the accuracy of the established model was verified.

II. DESIGN AND FABRICATION

The design and manufacture of the soft actuator are introduced in detail in the paper [32]. The entire soft actuator is made of soft material silicone. The modular design and its convenience to combine to soft arm is the main novelty of this new type soft actuator. Figure 1 (A) shows the working principle of the soft actuator. Three elastic air chambers are radially distributed inside the soft actuator. By changing the pressure of the driving fluid in the three chambers, the soft actuator can achieve bending in the corresponding direction or elongation of the actuator in the axial direction. Because the actuator is made of a soft material, silica gel, the enclosure expands in all directions as the drive fluid is filled.

Figure 1 (B) shows the schematic diagram of radial restraint in the form of left-right symmetrical double spiral winding in this design, and the winding angle of the fiber is ±3°. In this way, the radial expansion of the elastic inner chamber can be restricted. When the interior is filled with fluid, the elastic air chamber only extends in the axial direction.

Figure 2 (C) shows the main structure of the drive:
1) High elastic silicone molded driver matrix; Closed elastic chamber;
2) The fiber limiting layer that restricts the radial direction of the elastic chamber;
3) Connector block made of ABS material;
4) Joint seal cover molded by high hardness silica gel.

The manufacturing of the designed software driver mainly uses a multi-step molding process, which mainly includes four processing steps, as shown in Figure 1 (D).

I: The inner layer of the elastic chamber is molded. First, the chamber core and chamber casting mold were 3D printed with (ABS) material, and the inner layer elastic air chamber with a thickness of 1.5mm was cast with low-hardness silica gel.

II: The aramid fire layer envelope. Kevlar fibers were used to envelop the inner elastic chamber and restrain the radial expansion of the inner elastic air chamber.

III: The actuator matrix molding. Insert the fiber-encapsulated elastic chamber into the positioning hole of the chassis of the casting mold, and cast the main part of the actuator base body with low hardness silicone. After curing,
the joint connecting part of the soft actuator base body is cast with high hardness silicone.

IV: The actuator end seal encapsulation. Fix the joint connector with silica gel adhesive to the actuator matrix after stripping, and finally cast the joint seal cover with high hardness silica gel.

III. MECHANICAL MODELING

As mentioned in the introduction, many models for deformation are based on finite element method or experimental test. As one main innovation of this work, we presented a simple mechanical model based on lumped parameter force analysis. It is simple in structure and can be conveniently used in control.

A. EXTENSION

The final attitude of the soft actuator is determined by the force balance inside the actuator. When the actuator is stretched, the tension stress between the gas pressure and body material is balanced:

\[
pA = \sigma A' \\
A_0 = A + A'
\]

where A is the projected area of the air chamber, A' is the projected area of the actuator body material, d is the pulling stress, and p is driving gas pressure.

According to material mechanics:

\[
\sigma = E\varepsilon = E \frac{\Delta L}{L}
\]

where E is the elastic modulus of the actuator, \( \Delta L \) the elongation of the actuator, and L the initial length of the actuator.

According to equations (1), (2), and (3), the relationship between the elongation and driving gas pressure is established:

\[
\Delta L = \frac{LA}{E(A_0 - A)}p
\]

Equation (4) above shows the relationship between the driving pressure and the elongation of the actuator. It is noteworthy that the effect of the gravity on the actuator is ignored in the equation above. In addition, the elastic modulus is not a constant value. The test method was used in this study for calibration.

Subsequently, considering the effect of gravity on the elongation of the actuator, the deformation of equation (1) is as follows:

\[
pA = \sigma A' \pm \frac{\Delta L}{L + \Delta L}G
\]

In the formula above, the second term considers the gravity effect of the elongated portion of the soft actuator.

By combining the formulas above, the relationship between the driving pressure and the elongation of the actuator considering the effect of gravity can be obtained as follows:

\[
pAL(L + \Delta L) = \Delta L(L + \Delta L)EA' \pm \Delta LLG
\]

Equation (6) is a nonlinear quadratic equation of elongation.

B. BENDING

Similarly, the bending posture of the soft actuator is determined by force balance. During bending, the gas pressure on some cavities is balanced with the tensile stress of the body material.

The relation between driving pressure and actuator elongation has been deduced previously. Now, it is necessary to establish a correlation with the bending angle. Hence, the following are assumed:

1. The chamber is elongated when the left inflation chamber is inflated;
2. The length of the middle part of the corresponding right chamber of the soft actuator does not change, as shown in Figure 3 (a).

Based on the two assumptions in Figure 3 (a) above and subsequently according to Figure 3 (b), the elongation of the elongated side during bending can be calculated as follows:

\[
(L + \Delta L) - L = \left( R + \frac{3}{2}R_q \right) \theta - R\theta
\]

The following simplification can be obtained:

\[
\Delta L = \frac{3}{2}R_q \theta
\]

Equation (8) shows the relationship between the driving bending angle and the elongation of the actuator. Similarly, the gravity of the actuator is ignored in the equation above. Next, the effect of gravity on the bending angle of the actuator is considered.

In the following analysis, assuming that the actuator is in an inverted suspension state, gravity acts on the actuator as a force opposite to the bend when the actuator is bent, thereby creating a torque to the actuator, as shown in Figure 3(b).

In the analysis below, it is assumed that the actuator is hung upside down. When the actuator is bent, the actuator gravity
acts on the actuator as a force opposite to the direction of
the bend, which creates a moment on the actuator, as shown
in Figure 3(c).

The gravity moment is calculated by integration, which can
be derived from the figure above:

\[ L_G = \int_0^\theta \rho g ds R (1 - \cos \theta) \]
\[ = \int_0^\theta \rho g R (1 - \cos \theta) Rd\theta \]
\[ = \rho g R^2 (1 - \sin \theta) \]  

where \( L_G \) is the bending moment of gravity on the actuator,
\( \theta \) the actuator bending angle, \( R \) the bending radius of the
actuator, \( \rho \) the soft actuator linear density, and \( G \) the soft
actuator’s own gravity.

\[ G = \rho g R \theta \]  

Therefore, the gravity moment is

\[ L_G = \frac{G}{\theta} R (\theta - \sin \theta) \]
\[ = GR \left( 1 - \frac{\sin \theta}{\theta} \right) \]  

According to the geometric relationship in Figure 5(c),
the bending moment of the resultant end of the actuator can
be obtained:

\[ L_S = 2R \sin \frac{\theta}{2} \sin \frac{\theta}{2} \]  

The actuator torque balance equation is

\[ (F_S - F_K) L_S - M_G = 0 \]  

where \( F_K \) is the tensile force generated by the body material
when the actuator is stretched, \( F_s \) the driving elongation
force generated by the driving pressure, and \( L_S \) the bending
moment arm of the combined force at the end of the actuator.

Integrating the equations above, the actuator torque bal-
ance equation can be obtained:

\[ (pA - EA \frac{1}{L} \frac{\theta^3}{3} R_0) \left( 1 - \cos^2 \frac{\theta}{2} \right) - G \left( 1 - \frac{\sin \theta}{\theta} \right) = 0 \]  

It is clear that equation (14) is a nonlinear equation per-
taining to the bending angle of the actuator, which requires a
numerical solution.

In the mechanical model above, the elastic modulus of the
actuator varies with the actuator shape variable; therefore,
it is necessary to calibrate the elastic modulus of the actuator
experimentally.

IV. EXPERIMENT AND DISCUSSION

A. TEST PLATFORM OF SOFT ACTUATOR

Figure 4 shows the test scheme of the soft actuator. Differ-
ent actuator actions can be realized by independently con-
trolling the gas pressure of each elastic air chamber. Three
proportional solenoid valves (SMC ITV003-2BL) enable the
independent adjustment of the driving pressure of each air
chamber. The Advantech PCI-1727 acquisition board was
used to control the output pressure of the three pressure-
regulating valves with three analog outputs (voltage). A
human–computer interface established by Labview was used
to directly input the preset pressure value and driving time
range of each chamber.

The system above was used to test the bending and elon-
gation characteristics of the soft actuator. During the bending
angle test, the single air chamber and two air chambers were
pressurized separately, and the driving pressure was from 0 to
2 and 0.2 bar at every other test point. When the bending
angle was tested, the same pressure was applied to all three
air chambers simultaneously. Table 1 below shows the initial
geometry parameters of the actuator.

B. ELASTIC MODULUS CALIBRATION OF THE ACTUATOR

The elastic modulus of the soft actuator varies with the shape.
Although the soft body of the actuator was made of elastic
silicone, to limit the radial expansion of the actuator, a tensile
fiber was wound around the air chamber of the actuator,
which distinguished the mechanical properties of the actuator
from the S-shaped characteristics of hyperplastic materials.
It is difficult to accurately describe the relationship between the driving pressure and the deformation of the soft actuator based on theoretical analysis. Therefore, the elastic modulus of the soft actuator was experimentally. To test the elastic modulus of the actuator more accurately, the test result of the actuator elongation was used to calibrate the elastic model. The elastic modulus of the actuator should theoretically be unaffected by gravity; therefore, the actuator should be placed horizontally during the test to eliminate the effect of the actuator’s gravity. Figure 5(a) shows a graph indicating the relationship between the elongation of the actuator and the driving pressure obtained from the test.

As shown from the graph, with the increase in driving pressure, the actuator elongation increases nonlinearly. Here, the elongation test curve is fitted as a quadratic polynomial:

$$\Delta L = ap + bp^2$$  \hspace{1cm} (15)

Combined with equation (4), the relationship between elastic modulus and driving pressure can be obtained:

$$E(p) = \frac{LA}{(A_0 - A)(a + bp)}$$  \hspace{1cm} (16)

Figure 5(b) shows a graph indicating the relationship between the elastic modulus of the actuator and pressure. As shown, as the driving pressure of the actuator increases, the elastic modulus of the actuator decreases nonlinearly.

When the driving pressure is 0, the actuator has a modulus of elasticity of $1.75 \times 10^5$ Pa, and when the driving pressure is increased to 2.0 bar, the actuator elastic modulus decreases to $1.23 \times 10^5$ Pa.

By substituting equation (15) into the mechanical model (6) and (13) of the actuator elongation and bending, the mechanical models of the actuator with variable elastic modulus can be obtained.

C. BENDING TEST

Figures 6 show the theoretical calculation and experimental test results of bending angle of the soft actuator when a single chamber and double chambers are charging, respectively.

Figure 6 (a) shows the theoretical calculation and experimental results of bending angle of the actuator when a single chamber and double chambers are charging, respectively. In this experiment, one of the three chambers was inflated and the driving pressure ranged from 0 to 2.0 bar.

In the theoretical calculation, the two cases of considering/not considering the effect of gravity were considered separately. As shown from the figure, when the actuator was pressurized in a single chamber and the driving pressure
was 2.0 bar, the bending angle of the actuator could reach 78°, and the bending angle of the actuator increased almost linearly with the increase in the driving pressure, indicating the good linearity of the soft actuator. This was because the fiber constraint layer outside the elastic chamber limited the radial expansion of the elastic chamber, thereby resulting in the full utilization of the filled gas for the axial elongation of the chamber.

When the effect of gravity was neglected, the calculation results agreed well with the test results, i.e., within the range of the measurement error, especially when the driving pressure was less than 1.0 bar. When the driving pressure exceeded 1.0 bar, the difference between the theoretical and test results increased gradually to a maximum of 10°. However, in general, the theoretical calculation could describe the bending deformation characteristics of the actuator when it was charged with a single chamber. When gravity effects were included, the theoretical calculations were closer to the test results, especially when the driving pressure was less than 1.0 bar, which was almost coincident. Therefore, the mechanical model of the actuator, which included the effects of gravity, demonstrated a higher accuracy.

Figure 6 (b) shows the theoretical calculation and experimental results of bending angle of the soft actuator with the change in driving pressure when the double chamber was inflated. As shown, when the driving pressure reached 2.0 bar, the bending angle of the actuator could reach 81°.

Similar to the single chamber inflation of the actuator, when the driving pressure was less than 1.2 bar, the theoretical calculation results were within the error range of the experimental test curve. When gravity effect were included, the theoretical calculation was closer to the test result. After the pressure exceeded 1.2 bar, the difference between the theoretical value considering gravity effects and the experimental test value was small; therefore, the mechanical model could describe the characteristics of bending deformation of the actuator more accurately.

**D. FORCE TEST**

Next, the maximum allowable load force of the actuator was tested, and the test scheme is shown in Figure 7. When testing the maximum allowable load force at the end of the actuator, the actuator must be fixed in the initial position. Therefore, when the actuator was bent, the force sensor was used to hold the actuator side in the initial position and the other side of the actuator was inflated, as shown in Fig. 7(a). When the actuator was stretched, the force sensor was used to hold the actuator from the top to ensure that the actuator remained at the initial length when the three air chambers were simultaneously inflated, as shown in Figure 7(b).

Figure 8(a) shows the maximum allowable load force curve of the actuator when the single chamber was inflated and deflated. During inflating, when the driving pressure was 0.1 bar, the actuator began to have an allowable load force of 0.8 N. As the driving pressure continued to increase, the maximum allowable load force of the actuator increased almost linearly. When the driving pressure reached 2.0 bar, the maximum allowable load force of the actuator reached 4.8 N. During pressure release, under the same driving pressure, the maximum allowable load force of the actuator was slightly smaller than that during inflating, and hysteresis appeared. This may be owing to the characteristics of silicone, the structure of the actuator’s inflatable chamber, and other reasons, which are worthy of further discussions.

Figure 8(b) shows the maximum loading forces curve of the actuator when the double chamber was inflated and deflated. When the driving pressure was 0.1 bar, the actuator began to have an allowable load force of 0.9 N. As the driving pressure continued to increase, the maximum allowable load force of the actuator reached 5.2 N. However, when actuating two chambers simultaneously, the linearity of the maximum allowable load force was much lower than that achieved when actuating a single chamber with the same pressure. As shown
in Fig. 8(b), when increasing the driving pressure, the slope of the force characteristic curve first increased and subsequently decreased by a small amplitude. In addition, when the double air chamber was inflated, the maximum allowable load force at the end of the actuator was slightly smaller than that at the time of charging, and hysteresis appeared as well.

When the three air chambers of the actuator were simultaneously inflated, the actuator extended, and the output force was the outward extension force along the axis of the actuator. To measure the maximum allowable load force under such conditions, a force sensor was used to support the actuator from the end of the actuator to ensure that the actuator remained at the initial length when three cavities were simultaneously charged. Figure 8(c) shows the maximum allowable load force curve at the end of the actuator when the three chambers were inflated and deflated. When the driving pressure was 1.0 bar, the maximum allowable load force could reach 44 N and increase linearly with the driving pressure. In addition, hysteresis appeared during pressure inflation and deflation.

V. CONCLUSION

Herein, we first introduced the design and fabrication of a new modular fluid-driven soft actuator that could complete three-degrees-of-freedom motions, including
omnidirectional bending and axial elongation. Such an actuator exhibits strong environmental adaptability. Subsequently, based on the principles of material mechanics and experimental test data, a simplified mechanical model of the new soft actuator was established considering the gravity effect. An experimental test rig was designed to verify the performance of the soft actuator prototype by comparing it with the proposed mechanical model. The proposed model is simple than the existing FEM models, and easier to apply in control modules.

Finally, the following conclusions can be summarized:
1) The maximum bending angle of the actuator could reach 80° when inflating in the single and double air chambers, and the elongation of the actuator could reach 23.6% when inflating in the three cavities simultaneously.
2) As the driving pressure increased, the bending angle and elongation of the actuator increased with good linearity, which was beneficial for the control of the soft actuator.
3) The elastic modulus of the actuator was calibrated experimentally as a quadratic function of the driving pressure, and the effect of gravity on the deformation of the actuator was included in modeling. The derived mechanical model yielded results that were close to the experimental test results and exhibited high accuracy.
4) When the driving pressure was between 0.1 and 2.2 bar, the maximum allowable load force at the end of the actuator exhibited good linearity. At the same driving pressure, the maximum allowable load force during charging was larger than that during pressure release; therefore, hysteresis appeared, which was present in both single- and double-chamber driving.

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