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# A study on the design of an inflatable manipulator based on a potential energy fields

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## Abstract

In this paper, the dynamic characteristics of an inflatable manipulator based on the potential field was explored. To this end, a elephant trunk-like inflatable soft manipulator is designed and its dynamic modelling analysis is explored. First of all, the mechanical structure is designed based on the principle of using different elastic materials under the same stress and causing the local strain difference to make the material bend. Then, based on the Yeoh model, the strain energy density function of the superelastic material is established. By calculating the elastic potential energy as well as the gravitational potential energy of the soft manipulator, and using the Lagrange method, the general equation of dynamics is obtained. Finally, different envelope space is obtained by changing the pressure value of the inner cavity by bending. The results show that the stress uniformity can be applied to the non-destructive gripping operation condition.

**Keywords:** soft robot, mechanics modelling, inflatable, trunk-like

## 1. Introduction

With its unique advantages, the soft robot has attracted the attention of scientists, but its research is still in its infancy, and there are still some problems to be solved in dynamic modeling and analysis. Related research shows[1-2]that with the development of materials chemistry, robotics, bionics, chemistry, micro-electromechanics, control theory, etc. soft robots have attracted the attention of many scholars with its continuous deformation, infinite freedom in theory, good adaptability to the environment and many other features. As a result, Chembots [3], Blob bot [4], ChiMERA [5], GoQBot [6] and other unique soft robots have been developed. However, it is undeniable that the related research of soft robots is still in the exploration stage, and its development still faces many difficulties and challenges. The purpose of this paper is to study an inflatable manipulator and to do dynamic modeling and analyze.

## 2. Manipulator structure

In this paper, an inflatable soft manipulator uses the local strain difference of different materials to produce bending freedom. The section is shown in Fig.1. The inflatable manipulator is composed of three identical fan-shaped softs, and its three-dimensional structure is shown in Fig.2. The bending angle of the finger part is proportional to the air pressure in the cavity. It is assumed that the length of the non-retractable body remains unchanged during the inflation process, and the elastic body is compressed and expanded to complete the finger bending action.

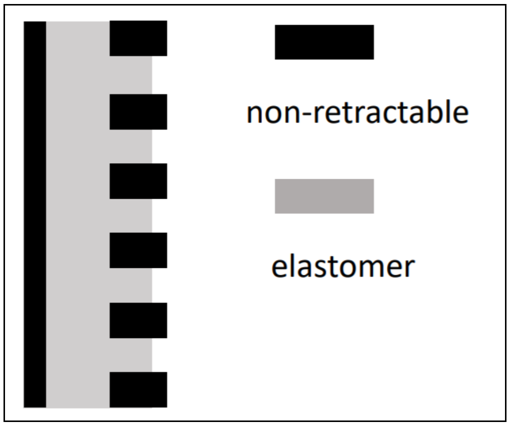

**Fig 1:** The schematic diagram of the inflatable soft manipulator

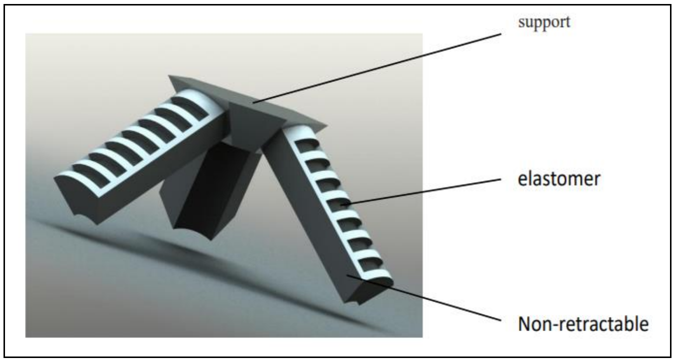

**Fig 2:** Three-dimensional model of soft manipulator

## 3. Mechanical model of potential field

### 3.1 Elastic potential energy of a soft robot

The establishment of dynamic models is of great significance for the structural optimization of soft robots. In this paper, the soft manipulator is similar to a highly flexible line-driven continuum robot, and the dynamics of the soft manipulator is analyzed by the Lagrangian method. For a pneumatic soft robot, its energy includes not only the gravitational potential energy but also the elastic potential energy. The two energy source outputs are converted into kinetic energy to change the shape of the manipulator.

Since the vulcanized molecules of the rubber material form a network structure, they have properties such as superelasticity and incompressibility$\left(J_3=1\right)$. Therefore, for a soft robot made of silica gel, it can be approximated as uniaxial stretching. Consequently, the strain energy density function can be derived based on the Yeoh model. Assuming that the rubber material is isotropic and incompressible, its deformation energy storage function is

$$\mu=\mu\left(J_1, J_2, J_3\right)$$

and

$$\begin{aligned} J_1 &= \lambda_1^2+\lambda_2^2+\lambda_3^2 \\ J_2 &= \lambda_1^2\lambda_2^2+\lambda_2^2\lambda_3^2+\lambda_3^2\lambda_1^2 \\ J_1 &= \lambda_1^2\lambda_2^2\lambda_3^2=1 \\ \lambda_i &= \gamma_i+1,\ i=1,2,3 \end{aligned}$$

where $J_1, J_2, J_3$ are tensor invariants, $\lambda_1,\ \lambda_2,\ \lambda_3$ are main elongation ratios, $\gamma_i$ is primary strain.

The typical two-parameter form of the Yeoh model can be expressed as

$$\mu=\sum_{i=1}^{2} C_i\left(J_1-3\right)^i \text{。}$$

where $J_1$ is the first invariant of the stress tensor, $C_1, C_2$ are independent elastic constants.

Silicone material is not compressible, so When it is under pressure $\lambda_3=1$ and $\lambda=\lambda_1=\frac{1}{\lambda_2}$. The first invariant of the stress tensor can be expressed as

$$J_1=\lambda^2+\frac{1}{\lambda^2}+1$$

Therefore, the energy density function is

$$\mu=C_1\left(\lambda^2+\frac{1}{\lambda^2}-2\right)+C_2\left(\lambda^2+\frac{1}{\lambda^2}-2\right)^2$$

Where the independent elastic constant is taken

$$C_1=0.11, C_2=0.02 \text{。}$$

The elastic potential energy is an integral of the energy density function

$$U_e=\int_0^R\int_0^\pi \mu\left(\lambda\right)\lambda L\tau d\tau d\alpha$$

Where $\mu\left(\lambda\right)$ is the strain energy density function of the silica material in the Yeoh model, R is the radius of the soft manipulator, ***L*** is the length of the non-elastic body of the soft manipulator, $\lambda$ is the main elongation of the soft manipulator.

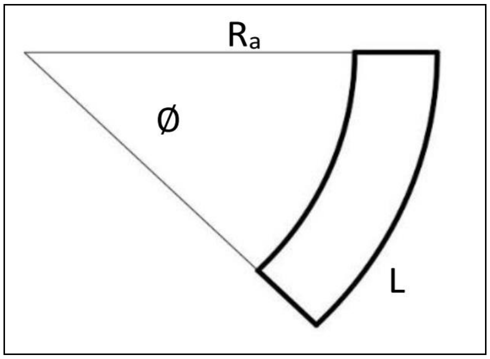

**Fig 3:** Soft monomer deformation

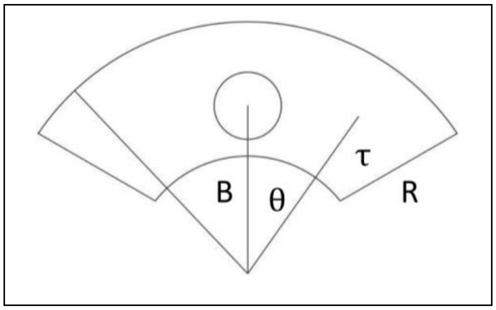

**Fig 4:** Monotonous deformation cross section

From the figure, the main strain $\gamma$ of cross section is,

$$\gamma_{\tau,\ \theta}=\frac{R'+\tau\sin\theta}{R'}$$

and $R'=L/\phi$, so

$$\gamma_{\tau,\ \theta}=1+\frac{\phi\tau\sin\theta}{L}$$

So

$$U_e=\int_0^R\int_0^\pi \mu\left(\lambda\right)\left(1+\theta\cdot\tau\sin\alpha/L\right)L\tau d\tau d\alpha$$

In this formula

$$\mu(\lambda) = C_1\left(\lambda^2 + \frac{1}{\lambda^2} - 2\right) + C_2\left(\lambda^2 + \frac{1}{\lambda^2} - 2\right)^2$$

$$= C_1\left[\left(1+\theta \cdot \tau \sin \alpha / L\right)^2 + \frac{1}{\left(1+\theta \cdot \tau \sin \alpha / L\right)^2} - 2\right]$$

$$+ C_2\left[\left(1+\theta \cdot \tau \sin \alpha / L\right)^2 + \frac{1}{\left(1+\theta \cdot \tau \sin \alpha / L\right)^2} - 2\right]$$

3.2 The gravitational potential energy of the soft manipulator

From the force analysis, the centroid M of the software manipulator is approximated to be at its axis. In the generalized coordinate system, the centroid M of the software manipulator can be represented by the bending angle θ.

$$P_n(x_p(\theta),\ y_p(\theta),\ z_p(\theta))$$

In this formula

$$x_p(\theta) = \frac{L \cos \phi (1 - \cos \theta)}{2\theta},$$

$$y_p(\theta) = \frac{L \cos \phi (1 - \cos \theta)}{2\theta},$$

$$z_p(\theta) = \frac{L \sin \theta}{2\theta},$$

The gravitational potential of a soft robot is

$$U_g(\theta) = mgz_p(\theta)$$

In summary, the potential energy of the software robot is

$$U = U_g + U_e$$

For conservative systems, the generalized force is

$$Q = \frac{\partial \mu}{\partial \theta}$$

Using the isochronous variation of generalized coordinates to represent the virtual displacement of each particle. From the general equation of dynamics, the kinetic energy of the particle system is

$$T = \sum_{n-1}^{N} \frac{1}{2} m_n \frac{d}{d_t} P_n \square \frac{d}{d_t} P_n$$

For a complete system without redundant coordinates, the generalized coordinate number is equal to the degree of freedom. According to the Lagrangian method, the general equation of dynamics is obtained. The Lagrangian operator L=T-V, the Lagrangian method for generalized coordinates can be written as:

$$\frac{d}{d_t}\frac{\partial L}{\partial \theta} - \frac{\partial L}{\partial \theta} = Q - b\theta$$

Where b is damping coefficient, and it represents the non-conservative properties of the generalized force of the system. Simplified formula

$$C\left(\theta, \dot{\theta}\right)\dot{\theta} + H\left(\theta\right)\ddot{\theta} + G\left(\theta\right) = B\tau$$

Where $C\left(\theta, \dot{\theta}\right)\dot{\theta}$ is coriolis force and centrifugal force, $H\left(\theta\right)\ddot{\theta}$ is

Inertia force term, $G\left(\theta\right)$ is Gravity, The right side of the equation is the damping coefficient matrix.

4 Simulated analysis

The soft robot is an important tool for grasping and clamping. Especially in the fruit picking process, the rigid robot is difficult to control its strength and easily damage the tender skin. The soft manipulator is ideal for automated picking robot end gripping tools due to its large deformation and unlimited degrees of freedom.

Based on the kinetic model, Abaqus simulation is used. The shape of the soft manipulator is shown in Fig. 5 when the air pressure is 30Mpa. It can be seen that a principle of an inflatable manipulator is feasible and has certain scientific research value.

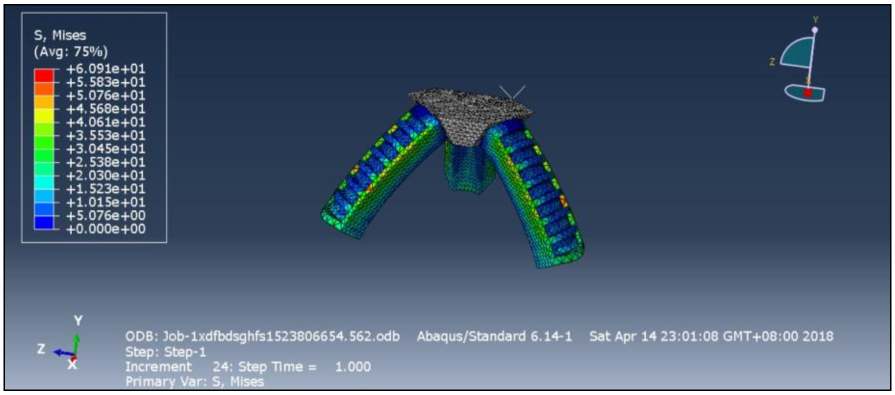

**Fig 5:** Abaqus clamping simulation at 30Mpa

## 5. Conclusion

1. Under the same stress, the local strain difference generated by different elastic materials can cause the material to bend, and the principle has certain feasibility.
2. For the inflatable soft manipulator, the dynamics modeling based on Yeoh and Lange Lange equations has a certain reference for practical applications.
3. Through Abaqus simulation, it was found that the designed soft robot can effectively complete the clamping task of irregular shape.

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