

¹Ping Zhang
²Qiang Zhang
³Mingjun Sun
^{4*}Hezhe Zhang

Dynamic Modeling and Grasping Application of a Cable-Driven Soft Actuator



Abstract: - Soft actuators are widely studied and utilized owing to their advantages in terms of compliance, safety, and adaptability. Because of the diversity in design of actuators and strong nonlinearity of materials, it is a challenge to establish an accurate dynamics model. In this paper, a cable-driven soft actuator is proposed, and the flexible multibody systems method is used to analyze the dynamics. The reasonability of the dynamics model was verified experimentally. Moreover, a four-finger soft gripper is designed based on the proposed actuator, and the wide applicability and potential application of the gripper are demonstrated.

Keywords: Soft actuator, Dynamic modeling, Grasping application.

I. INTRODUCTION

Soft actuators have made significant progress over the past few decades [1-4]. With the development of elastic and smart materials, soft actuators have inherent advantages in terms of safety and compliance compared with traditional rigid robotics. Hence, the soft actuators have broad application space and huge development potential. Soft actuators made of soft materials theoretically have infinite degrees of freedom, so it is a challenge to establish an accurate dynamics model. Many researchers have made efforts in establishing models of soft actuator, and the main methods including piecewise constant curvature model, Lagrange equation method, Cosserat rod theory, and finite element method. For example, Mahl et al. [5] divided soft actuators into sever segments using piecewise constant curvature method, and then the kinematic model of soft actuator was established. Wang et al. [6] carried out servo control of soft actuators based on the piecewise constant curvature model. Thieffry et al. [7] proposed a linearized dynamic modeling method of soft robot through Lagrange equation method. Recently, Liu et al. [8] established a new dynamic model for a cable-driven actuator. On the basis of the Cosserat theory, Giorelli et al. [9] established a two-dimensional kinematic model of a cable-driven octopus arm and explained the large deformation mechanism of the soft arm. Besides, Gu et al. [10], Heung et al. [11], Bieze et al. [12], and Polygerinos et al. [13] used the finite element method to study the bending process, the overall performance and the internal interaction of pneumatic soft actuators.

It can be seen that the dynamics of soft actuators have been widely studied. Different modeling methods are developed for soft actuators with different structures and different driving methods. Herein, the design of a cable-driven soft actuator with triangular cuts was proposed, and the dynamics model was established using the concept of flexible multibody systems. And then, the effectiveness and accuracy of the model were verified through experiments. Finally, the application of the soft actuator in grasping was demonstrated.

II. DESIGN OF THE ACTUATOR

The design of the soft actuator references our previous works [14]. The proposed actuator contains a group of linearly arranged elements separated by triangular cuts with an angle of $\alpha = 45^\circ$. A two-part addition type silicone rubber is used to fabricate the body, and the material characteristic parameters are listed in Table 1. The cable routing is straight through the holes with a diameter of 6 mm in the actuator body. The driving cable is made of polyethylene fibers and has a diameter of 0.5 mm. One end of the cable is fixed at the end of the soft actuator. The actuator performs bending motion by driving the cable. The schematic structure is shown in Fig. 1.

¹ College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao, 266000, China, E-mail: zhngpng@outlook.com

² College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao, 266000, China, E-mail: zhangqiangskd@sust.edu.cn

³ Zoomlion Heavy Industry Science&Technology Co., Ltd., Changsha, 410000, China, E-mail: sen1140624818@163.com

^{4*} Corresponding author: College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao, 266000, China, E-mail: 1103070190@qq.com

Table 1. Characteristic parameter of the silicone rubber

Property	Parameter
Density	1.12 g/cm ³
Shore hardness	20 ± 2 A
Tensile strength	4 MPa
Tearing strength	20 ± 2 kN/m
Elongation at break	≥500%

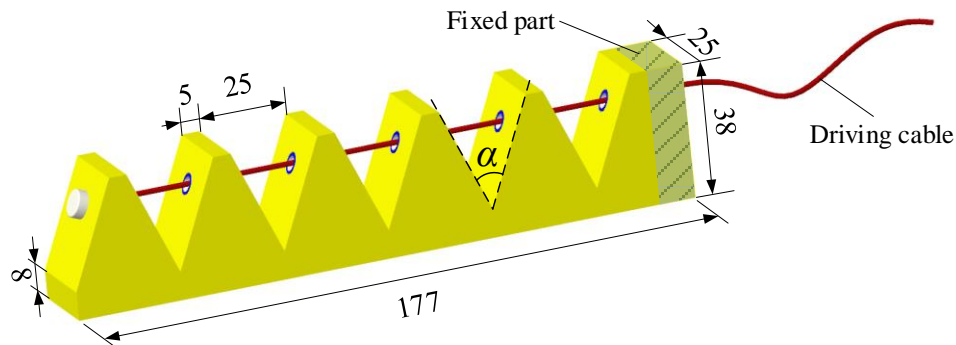


Fig. 1 Schematic structure of the actuator, unit: mm

III. DYNAMIC MODELING OF THE ACTUATOR

A. Physical Model of Flexible Multibody System

The actuator is divided into 6 elements named as B_1 - B_6 , and each element can be considered as an independent soft body, as is shown in Fig. 2(a)-(b). The element B_1 is fixed in an inertial coordinate system by an imaginary hinge h_1 . When the actuator bends under the driving force F_D , the connection relationship between two adjacent elements (h_2 - h_6) can be seen as a combination of column hinges and torsion springs (M_2 - M_6). The cable driving force can be simplified as F_1 - F_5 and M_B , as is shown in Fig. 2(c).

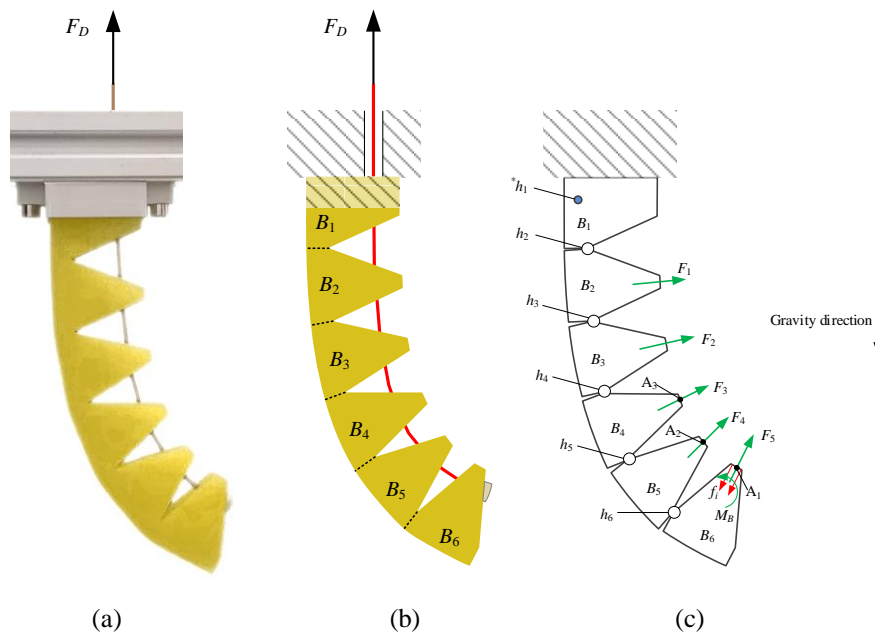


Fig. 2 Physical model analysis

B. Mathematical model of flexible multibody system

The Lagrange equation is used to describe the dynamic behavior of the soft actuator basing on the physical model. Considering the dissipative system, the Lagrange equation is given as

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_k} \right) - \frac{\partial L}{\partial q_k} + \frac{\partial \Gamma}{\partial \dot{q}_k} + \left[\frac{\partial \Psi}{\partial q_k} \right] \lambda = Q_k \tag{1}$$

where the L , Γ and Ψ are the Lagrangian function, dissipative function and constraint equation, respectively. λ and q_k are the Lagrange multiplier and generalized coordinates, respectively. Q_k is the generalized active force (that is, equivalent cable driving force) corresponding to the generalized coordinate q_k . The Lagrangian function $L = T - U$, where T and U are the kinetic energy and strain energy, respectively. For the proposed flexible multibody system, the strain energy U is the sum of the strain energy of the element (U_j) and the strain energy of the elastic joint (M_j), that is given as

$$U = \sum_{j=1}^6 (U_j + M_j) = \frac{1}{2} \sum_{j=1}^6 (\boldsymbol{\varepsilon}_j^T \boldsymbol{\Delta}_j \boldsymbol{\varepsilon}_j + \varphi_j^T K_j \varphi_j) \tag{2}$$

$\boldsymbol{\varepsilon}_j$ and $\boldsymbol{\Delta}_j$ are the modal coordinates of the soft element and diagonal matrix of natural frequency squared, respectively. φ_j and K_j are the joint rotation angle and torsion spring stiffness coefficient, respectively.

The kinetic energy T is given as

$$T = \sum_{j=1}^n T_j = \frac{1}{2} \sum_{j=1}^n \int v_j \cdot v_j dm \tag{3}$$

where v_j is the velocity of the infinitesimal mass (dm) of the soft element. The elastic displacement is obtained by modal superposition method. Submitting (2) and (3) in to the Lagrangian function, it can be obtained

$$L = \sum_{j=1}^n (T_j - U_j - M_j) \tag{4}$$

Submitting (4) into (1), the dynamic equation of the flexible multibody system is obtained.

IV. CALCULATION AND VERIFICATION

The commercial software ADAMS is used to repeat the above calculation process. Firstly, the modal neutral file of the elements is generated by ANSYS (APDL), which can express the elastic displacement by modal coordinates. As is shown in Fig. 3, each element has 3 outer connecting points, that is, points A_i , B_i , and C_i . The equivalent cable driving force is applied at points A_i , and B_i , and C_i are the connection points between adjacent elements. Secondly, the boundary condition of the flexible multibody system in ADAMS is shown in Fig. 4. The cable driving force $F_1 - F_5$ is applied on the outer connecting points $A_1 - A_5$, and the value of the applied force is determined by force analysis. And then, the total run time and time step are set as 2 s and 5×10^{-4} s, respectively. Finally, the dynamic simulation is conducted using the default solver, and the results are obtained by the post-processor. In addition, the main setting parameters are listed in Table 2.

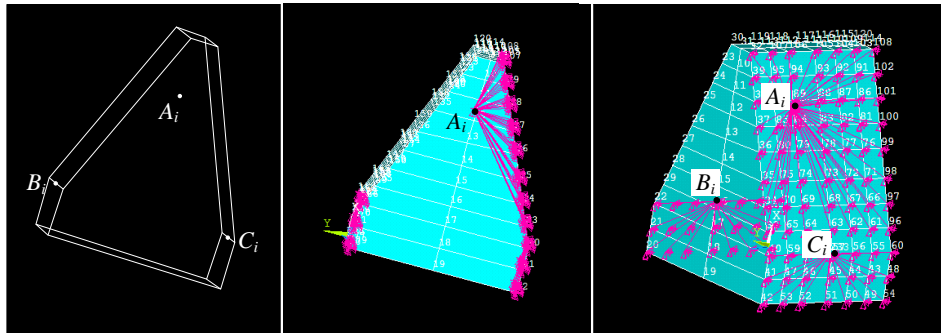


Fig. 3 The location of outer connection points

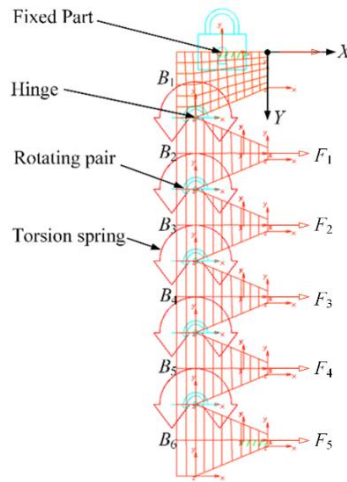


Fig. 4 Boundary condition setting in ADAMS

Table 2. Main setting parameters

Property	Parameter
Young's modulus	0.44MPa
Poisson's ratio	0.48
The number of modal orders	30
Modal damping	0.5
Torsion spring stiffness coefficient	1.9×10^{-3} Nm/deg
Torsion spring damping coefficient	10 Nms/deg

To verify the accuracy of dynamic modeling and simulation, the bending process of the soft actuator is tested experimentally. The comparison of simulation and testing results is shown in Fig. 5, where r is the cable shortening rate [14]. It is observed that the bending shapes in the simulations are similar to those in the experiments, which indicates the reasonability and effectiveness of the flexible multibody model.

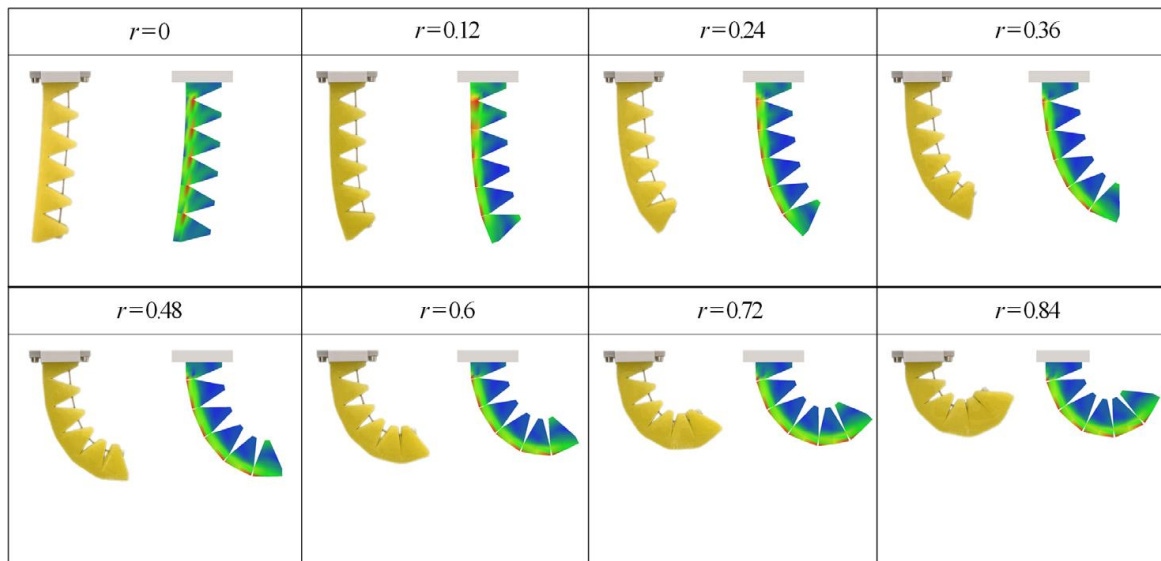


Fig. 5 Comparison of simulation and testing results of the bending process

V. APPLICATION OF THE ACTUATOR IN GRASPING

Grasping is an important function of soft robots, and enables them to collect and hold an object against external disturbances without damage. A soft gripper with four fingers is designed basing on the actuator. The practical photo and components of the soft gripper are illustrated in Fig. 6. It can be seen the end of the actuators are fixed on a 3D-printed rigid structure, and the cable routing is embedded in the rigid structure. One end of the driving cable is connected at the end of the actuator, and the other end is connected at the motor shaft. Thus, the actuators are actuated by four servo motors, and the cable contraction speed and cable shortening rate can be accurately controlled by the controller.

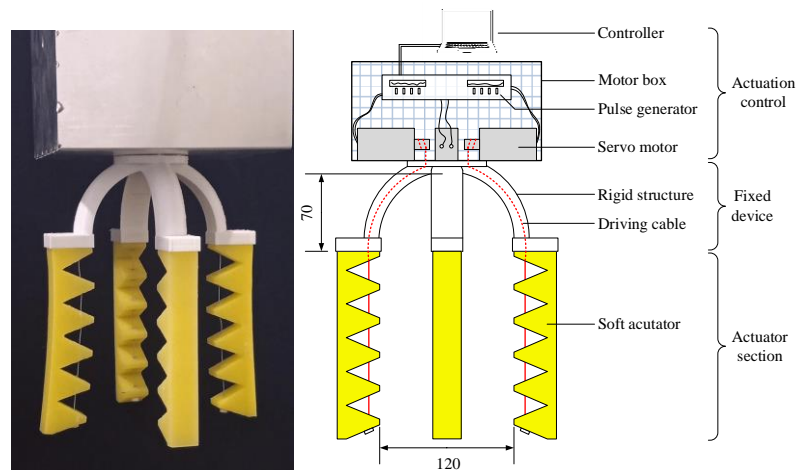


Fig. 6. The structure of the soft gripper

The grasping tests are carried out as shown in Fig. 7. It is observed that the proposed gripper can grasp a series of easily deformed and delicate objects, such as balloon, rectangular and cylindrical components, paper box, and plastic storage bag. It is indicated that the gripper has excellent gripping performance and great application potential in our daily life.

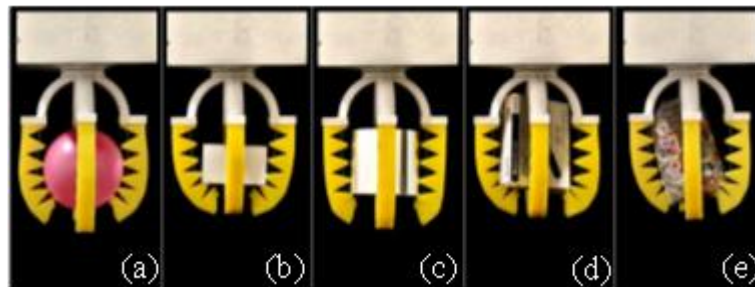


Fig. 7 Photographs of the soft gripper used for grasping multiple kinds of objects, including (a) balloon, (b) rectangular and (c) cylindrical structure, (d) paper box, and (e) plastic storage bag

VI. CONCLUSION AND DISCUSSION

In this article, a cable-driven soft actuator with triangular cuts was proposed, and the flexible multibody system modeling concept was used to study the dynamic characteristics. The physical model and mathematical model were firstly established, basing on which the software ADAMS was used to simulate the bending process. And then, the calculate results were verified experimentally, which indicates the reasonability of the dynamics model. Finally, a four-finger soft gripper was proposed, and its grasping status was displayed.

It is a challenge to establish an accurate model for soft actuators at present. We established a dynamics model based on the geometry structure and actuation method of the actuator. However, the flexible multibody systems method is not suitable for all soft actuators. Although the proposed model has a high accuracy in bending process of the actuator, the accuracy is not verified in actual working conditions (for example, the collision condition). The applicability of the model needs further exploration. The grasping ability, including gripping range, weight, and

grasping control, etc., is not presented in this article. Thus, future works include (1) improving the applicability of the dynamics model and adjusting it according to the actual situation and (2) testing the grabbing ability and performing servo control, so as to provide better applications.

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