Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Design and experimental validation of a cable-driven continuum manipulator and soft gripper

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***Abstract*—In this investigation, a cable-driven continuum manipulator as well as its soft gripper are designed and developed. The continuum manipulator is made up of two sections, including nine threading plates and eight spring steels. The four cables from the top to the end drive the Section I to bend and deform. The other four cables from the middle to the end drive the Section II to bend and deform. The grasping force and the wrapping area are both considering into the topological optimization process of the soft gripper in order to get a satisfying grasping performance. Moreover, the experiment system including the continuum arm, the soft gripper, and the cable-driven control mechanism is developed. The grasping performance of the soft gripper and the motion control of the continuum arm are validated experimentally.**

Keywords—continuum manipulator, cable-driven, soft gripper, design, experiment

I. INTRODUCTION

The soft manipulator is a special type of the soft robot. Its actuation mode determines its movement style. According to the actuation mode, the soft manipulator can be classified into gas-driven, cable-driven, magnetic-driven, and smart materials driven [1, 2]. The magnetic-driven mode requires external controllable magnetic, which is studied for its prospective in the minimally invasive surgery. The smart materials include Shape Memory Alloy (SMA), Shape Memory Polymer (SMP), and Electroactive Polymer (EAP). It is easy to downsize and its performance is largely determined by the improvement in materials [3]. The gas-driven mode provides the actuation force by pressure control and its advantages include responsiveness, ease of mobility, et al. However, the miniaturization of its pressure control system is still a challenge. The cable-driven mode provides the actuation by retracting the cable. It is also responsive and flexible. However, the cable control system is complex [4]. Currently, the cable-driven and the gas-driven modes are still the most popular choices. Sanan et al. [5, 6] designed a soft manipulator simulating human's arm. Voisembert et al. [7] presented a long range inflatable arm with cable-driven joints. Grissom et al. [8, 9] developed the OctArm to simulate the motion of elephant's trunk. Wang et al. [10, 11] presented a soft manipulator, which was made of silicone and driven by the cables. Kim et al. [12] proposed a foldable arm by implementing origami principle of perpendicular folding. Rafsanjani et al. [13] enhanced the crawling capability of a soft actuator by using harnessing kirigami principles. To model the soft manipulator, Sing et al. [14] developed a continuum model using Pythagorean Hodograph（PH）curve method. Hannan et al. [15, 16] developed the kinematical model of OctArm by using the Cosserat beam model and Mooney-Rivlin constitutive models. Jain et al. [17] carried out the design of the piezoelectric actuator for micro gripper. Mohamed et al. [18] presented a dynamic model for a micro-robot using Denavit–Hartenberg notations. Sanan et al. [19] studied the kinematics of a continuum arm with distributed compliance. Ishibashi et al. [20] developed a dynamical model of pneumatic joint using spring-damping model. Wang et al. [21, 22] developed a dynamic model of their rope-driven soft manipulator using Lagrange method. Currently, the design, fabrication and experiment are still the main concerns for the soft manipulator, the modeling and analysis are largely different according to different design. Therefore, the novel design and experiment is significant to the deep research on the soft manipulator.

In this paper, a cable-driven continuum manipulator and its soft gripper are designed and developed. The theoretical model of the continuum manipulator is proposed and the motion performance is analyzed. The topological optimization method is introduced into the design process of the soft gripper. In Section 2, the general design of the continuum manipulator system, the design of the continuum arm, and the topological optimization of the soft gripper is introduced. In Section 3, the experiment system of the continuum manipulator is developed. The capture test of the soft gripper and the motion control of the continuum manipulator is conducted to validate the performance of the experiment system. Finally, the conclusions are presented.

II. DESIGN OF A CABLE-DRIVEN CONTINUUM MANIPULATOR AND SOFT GRIPPER

A. General design schematic

The soft robot system is made up of a continuum arm, a soft gripper and a cable-driven control system. The continuum arm is driven by a series of cables and is able to bend flexibly. The soft gripper is also driven by the cable and is able to adapt

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the shape of the objects. The cable-driven control system includes numbers of motors and pulleys, which are all mounted on the frame and the base. The general design schematic is shown in Fig. 1.

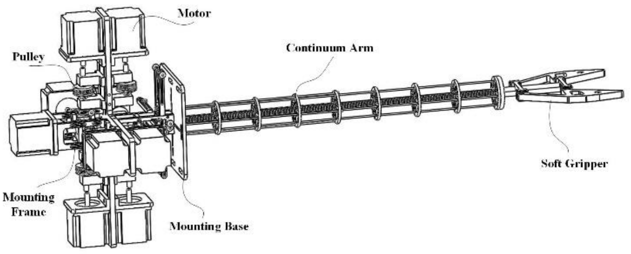


Fig. 1. General design schematic.

The continuum manipulator is made up of two sections, including nine threading plates and eight spring steels. Section I is from the top to the end, section II is from the middle to the end. The continuum manipulator is driven by eight cables. Thus, the continuum manipulator has eight control freedoms. The four cables from the top to the end drive the Section I to bend and deform. The other four cables from the middle to the end drive the Section II to bend and deform. The coupling effect of the two sections can make the continuum manipulator bend as "S" shape. The threading plate is made of aluminum, there are eight threading holes for the eight cables, and the mounting site for the connection of the springs.

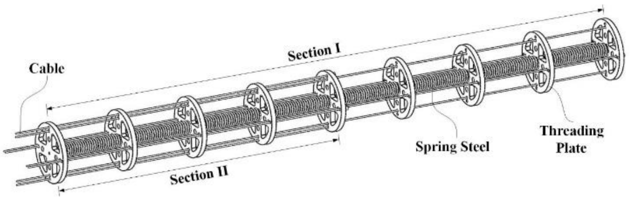


Fig. 2. Design of cable-driven continuum manipulator.

B. Topological optimization design of a soft gripper

It is known that human hands have an ability to grasp object with enough force and wrapping area. The force and wrapping area are two +important factors to determine the grasping performance. Thus, the output force and the output displacement are considered. In order to conduct the topological optimization design, two technical indexes, Mechanical Advantage (MA) and Geometry Advantage (GA), are defined. MA is the ratio of output force and input force, GA is the ratio of output displacement and input displacement. MA determines the grasping force while GA determines the wrapping area. The output force can be described using Mutual Strain Energy (MSE), and the output force can be described using structure softness (SE_o).

$$MSE = U_o^T K U_i \tag{1}$$

$$SE_o = \frac{1}{2} U_o^T K U_o \tag{2}$$

where, U_i is the displacement field produced by the input load, U_o is the displacement field produced by the output virtual load. The optimization objective function is presented as follows.

$$-\frac{MSE}{\omega SE_i + (1-\omega) SE_o} \tag{3}$$

where,

$$SE_i = \frac{1}{2} U_i^T K U_i \tag{4}$$

In order to describe the wrapping area more accurately, the divisional multi input and output method is introduced. The core concept is to divide the design area into numbers of small areas, in which the single input or output point is selected. Thus, the optimization objective function can be improved as follows.

$$-\frac{(1-\xi)\left(\frac{1}{mn}\sum_{i=1}^{n}\sum_{j=1}^{m} S_{mut1,ij}\right)+\xi\left(\frac{1}{pn}\sum_{i=1}^{n}\sum_{k=1}^{p} S_{mut2,ik}\right)}{2\eta\left(\frac{1}{n}\sum_{i=1}^{n} S_{in,i}\right)+2(1-\eta)\left[(1-\xi)\left(\frac{1}{m}\sum_{j=1}^{m} S_{out1,j}\right)+\xi\left(\frac{1}{p}\sum_{k=1}^{p} S_{out2,k}\right)\right]} \tag{5}$$

where, η is used to control the relationship between the mutual strain energy and the structure strain energy. ζ is used to control the weight relationship between two output areas. The number of input points is n, the numbers of output points in two output areas are separately m and p. The topological optimization design problem in this investigation can be described as follows.

$$\begin{cases} \min: -\dfrac{(1-\xi)\left(\frac{1}{mn}\sum_{i=1}^{n}\sum_{j=1}^{m} S_{mut1,ij}\right)+\xi\left(\frac{1}{pn}\sum_{i=1}^{n}\sum_{k=1}^{p} S_{mut2,ik}\right)}{2\eta\left(\frac{1}{n}\sum_{i=1}^{n} S_{in,i}\right)+2(1-\eta)\left[(1-\xi)\left(\frac{1}{m}\sum_{j=1}^{m} S_{out1,j}\right)+\xi\left(\frac{1}{p}\sum_{k=1}^{p} S_{out2,k}\right)\right]} \\ \text{s.t.:} \quad KU_1 = F_1 \; KU_2 = F_2 \; KU_3 = F_3 \\ \qquad \sum_{i=1}^{N} x_i V^e = V_f \\ \qquad 0 < x_{\min} < x_i < 1 \end{cases} \tag{6}$$

The topological optimization design process for the soft gripper is shown in the following.

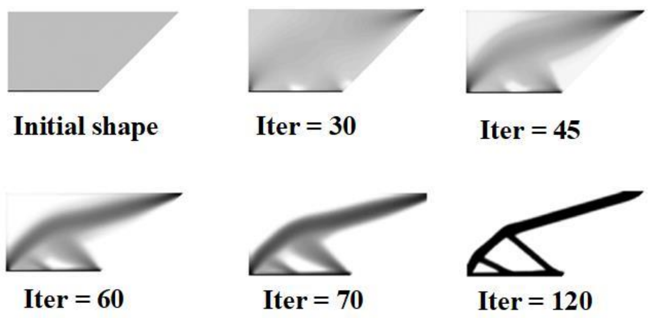
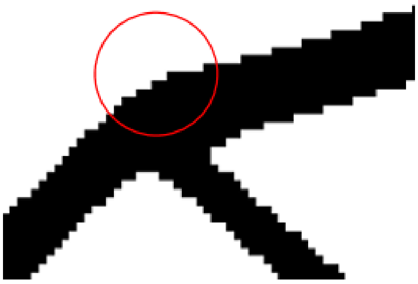
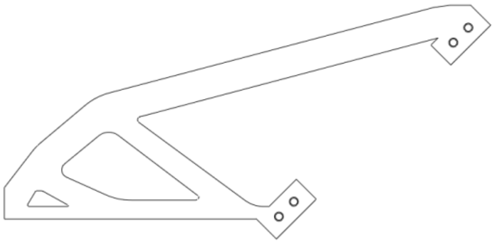


Fig. 3. Iterative process of topology optimization.

In the optimization process, the Zig-Zag phenomenon, which directly affects the three dimensional design of the structure, appears at the edge of the structure, as shown in Fig. 4(a). In order to obtain a smooth edge, the level-set method is adopted in the post-processing of the designed structure. Finally, the three dimensional structure of the soft gripper is obtained, shown in Fig. 4(b).



a. Zig-Zag Phenomenon.



b. three dimensional structure.

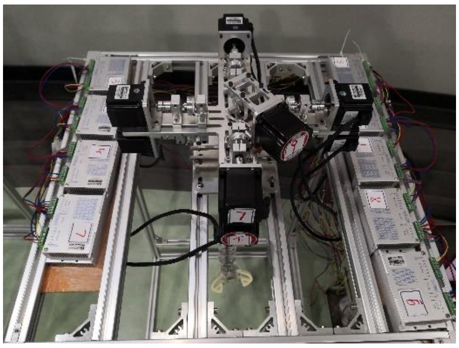
Fig. 4. Post-processing results.

III. EXPERIMENTAL VALIDATION

A. Experiment system

The experiment system of the continuum manipulator includes the continuum arm, the soft gripper, and the cable-driven control system, as is shown in Fig. 5(a). The continuum arm and the cable-driven control system are mounted on the aluminum frame with a suspension type. The cable-driven control system is shown in Fig. 5(b). The diameter of the continuum manipulator is 50mm. The diameter of the spring steel is 15mm, and the length is 50mm. The total length of the continuum manipulator is 450mm. The cable is made of steel and its diameter is 0.5mm. The maximum tension can reach to 30kg. The soft gripper is mounted at the end of the continuum arm. It is made by 3D print technology with TPU materials. The shore hardness of the TPU is D60. The capture test of the soft gripper and the motion control of the continuum manipulator will be performed in the following investigation.

a. prototype and experiment system.



b. control system.

Fig. 5. Experiment system.

B. Capture test of the soft gripper

The soft gripper is composed of two fingers, as is shown in Fig. 6. The grasp contact area of each finger is about 70mm $\times$10mm. The actuation displacement is about 35mm. When the soft gripper grasps objects, it can be seen that the fingers deform adaptively according to the shape of the objects, such as the water bottle, the egg, the table tennis, the motor, et al. As the increasing of the objects' weight, it can be seen that the adaptive deformation of the soft fingers increases. It is because the large structure deformation means the large force and wrapping area. In the following test, the weight from 3g (a table tennis) to 500g (a motor) are tested, shown in Fig. 6.

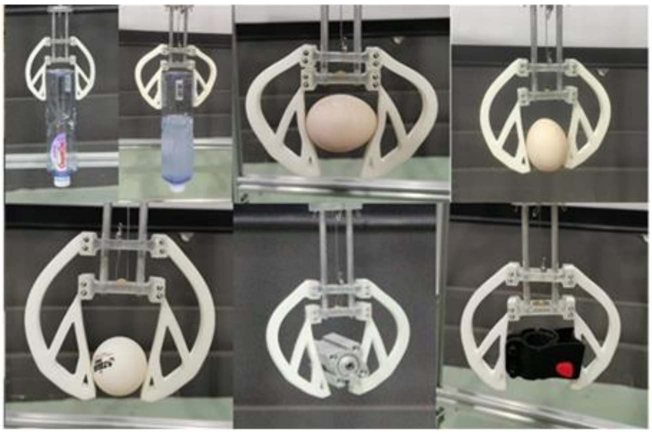
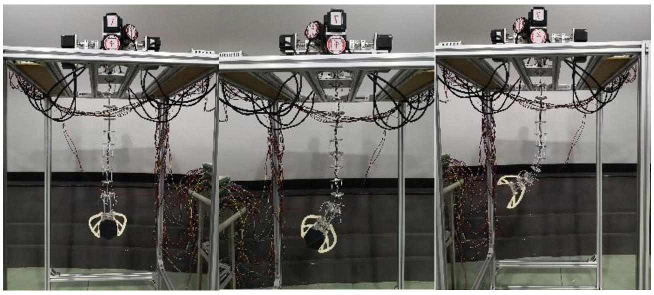


Fig. 6. Capture test of the soft gripper.

C. Motion control of the continuum manipulator

The continuum manipulator is driven using nine cables, in which eight cables are used to control the continuum arm and one cable is used to control the soft gripper. In Fig. 7(a), the motion control without payload is tested. It can be seen that the continuum manipulator can move according to different control patterns. In Fig. 7(b), the motion control with a payload of 200g is tested. It can be seen that the continuum manipulator has the ability to transport the object to different sites. Currently it is just validated that the continuum manipulator as well as the soft gripper are able to be controlled by the cable-driven control system. The deep research on the accurately modeling and control will be studied in our future work.

a. motion control without payload.



b. motion control with payload (200g).

Fig. 7. Motion control of the continuum manipulator: a. without payload, b. with payload (200g).

IV. CONCLUSIONS

In this investigation, a cable-driven continuum manipulator as well as its soft gripper were designed and developed. The cable-driven mode can provide a large control moment as well as a good motion flexibility. The coupling effect of the two actuation sections can make a complex movement pattern. The soft gripper is designed by using topological optimization method, and its final design structure is far different from the traditional result. It is validated that the soft gripper has a good grasping performance from the capture test results. The design and experiment of the soft gripper show us a wide prospective of the topological optimization method in the research of the soft robot. Currently, the continuum manipulator has only the ability to move according to the different pulling patterns of the cables. It is a big challenge for the current manipulator to keep stable during the motion control process. Next, the structure of the proposed continuum manipulator needs to get improved. The accurate model-driven control algorithm based on the kinematical and dynamical model of the cable-driven continuum manipulator will be studied in the future work.

ACKNOWLEDGMENT

The authors gratefully acknowledge the funding by the Postdoctoral Science Foundation and the Natural Science Foundation of China, under Grants No. 11702320, 11725211 and 61690213.

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