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Soft under-actuated hand with fin-ray structure

Cheng Zhao¹, Long Zeng²*, Minhe Chen¹, Yangbo Lin¹ and Jiayu Zhao¹
¹Mechanical Department, Tsinghua University, Beijing, China
²Graduated School at Shenzhen, Tsinghua University, Guangdong, China

*Corresponding author e-mail: zenglong@sz.tsinghua.edu.cn

Abstract. When the traditional under-actuated hands pinch the small objects, they tend to be unstable. To solve this problem, a new soft under-actuated hand is designed in this paper, which combines the soft fin-ray structure and the parallel under-actuated linkage mechanism. Compared with the traditional hands, the new design not only has the adaptive grasping mode, but also has the soft pinching mode, and through the pinching mode the small objects can be pinched stably. For tractable analysis, the design of the new hand is fully presented in this paper. Moreover, the force analysis and simulation are provided simultaneously. Finally, the experiments are conducted to verify the performance of the new design. The results indicate that the new hand could pinch small objects stably.

1. Introduction

The development of mechanical hand keeps a few decades. In order to meet the special needs in industrial, medical or service domain, there are many kinds of mechanical hand. Among them, the research of under-actuated mechanical hand is an important direction because it can adaptively grasp objects of different shapes.

The under-actuated hand using linkage mechanism is accurate and stable such as the SARAH robot hand[1] developed by LAVAL University and the ROBOTIQ gripper including two-fingers manipulator and the three-fingers manipulator[2]. To improve the performance of gripping small objects, some under-actuated hands use two transmission chains which are more complex, such as the parallel and under-actuated linkage mechanism developed by LAVAL University[3], and the parallel pinching and under-actuated hand developed by Tsinghua University[4]. The improved parallel pinching mode can stably hold small cubes or plates, but it is still difficult to hold small spherical or columnar objects. Pinching such objects with smooth surface is always a difficult problem in robot design[5,6], and some scholars keep studying on it through simulation[7].

In this paper, based on the existing parallel and under-actuated linkage mechanism, a soft fin-ray structure is introduced to improve the performance when under-actuated hand pinches small objects with curved surface.

2. Structural Design of soft under-actuated hand

2.1. Structure mechanism of the finger

The soft under-actuated finger has two gripping modes: soft pinching and adaptive enveloped grasping. As shown in Fig. 1, the soft under-actuated finger performs parallel movement before touching the object. If the end knuckle firstly touch the object, soft pinching is executed; if the first knuckle or the second knuckle touch the object firstly, adaptive enveloped grasping is executed.
The two gripping modes and parallel movement are achieved by a combination of rigid parallel-under-actuated linkage mechanism and soft fin-ray structure. The former realizes parallel movement and adaptive enveloped grasping, and the latter realizes soft pinching.

The parallel and under-actuated linkage mechanism [1] is shown in Fig. 2: the mechanism consists of two transmission chains: a parallel linkage mechanism and an under-actuated linkage mechanism. The entire mechanism has three degrees, consisting of one driven link and two springs.

The soft fin-ray structure [8] consists of rigid supporting rods in the middle, soft surface on both sides and the rotational joints between them. The effect is that when force is applied to one side, the structure will bend to this side and envelope the force as shown in Figure 2. Compared with other soft mechanisms, the fin-ray structure can withstand greater loads beneficial to the support of rigid rods in the middle.

In this paper, a new type of soft under-actuated finger is designed by integrating and improving two existing structures. The overall model of this finger is shown in Fig. 3. It has three knuckles. The stepper motor at the bottom (at the right side of the figure) provides the driving force for the entire finger. The crank-slider mechanism between the motor and the linkage mechanism converts slipping motion into rotation of the driving rods which belongs to under-actuated mechanism.

2.2. Whole hand design
Since the three fingers are the minimum number required to meet the complex holding gestures, the overall structure of the soft under-actuated hand designed in this paper is shown in Fig. 4 (a), which consists of three identical fingers and a palm structure. In order to hold objects of different shapes and sizes, the layout of three fingers needs to be properly adjusted. Therefore, the palm structure allows fingers to rotate within a certain range.

Fig.4 (b) shows these 3 kinds of layouts of the fingers. Meanwhile Fig.4 (c) shows the mechanism of the palm. A pair of four-linkage mechanism is adopted and it is driven by a servo and engagement gears. The positions of the two links in the Fig.4(c) are also the terminal positions of fingers in the Fig.4 (b). The size of the hand is designed refer to the human hand. The diameter of palm is 9cm.
3. Force analysis and simulation of fin-ray structure

As shown in Figure 1, parallel movement, soft pinching and adaptive grasping require at least two fingers to realize. However, while gripping an object, the gestures of each finger are totally same, so simulating and analyzing a single finger are enough.

3.1. Force analysis

The deformation of the fin-ray structure makes force analysis difficult. When the soft pinching is performed, the contact area between the fin-ray structure and the object is increased, so it is feasible to express the contact force through a set of distributed load, then take it as concentrated force.

A simplified force model is presented as shown in fig. 5(a). The radius of the ring is \( r \), and the contact area between the fin-ray structure and the ring is an arc with a central angle of \( \alpha \). The force applied from fin-ray structure to the ring is simplified to a uniform load, whose size is \( q \) and unit is \( \text{N/m} \), and all the directions point to the origin of the circle. The uniform load is equivalent to a concentrated force \( F_C \), and the relationship between \( F_C \) and \( q \) is derived by the following formula:

\[
F_C = \int_0^{\alpha} q \cos \theta \cdot r d\theta = 2qr \sin \frac{\alpha}{2}
\]

However, due to the particularity of the fin-ray structure, the force part is mainly concentrated in the vicinity of the rigid rod in the fin-ray structure, so it is more appropriate to equalize the uniform load to \( n \) concentrated forces, and the number of forces is equal to the number of rigid connecting rods in the contact area. As shown in Fig. 5(b), the uniform load is equivalent to 4 concentrated forces, each force is \( f_C \), whose direction points to the origin of the circle. The relationship between \( f_C \) and \( q \) is:

\[
f_C = 2qr \sin \frac{\alpha}{2}
\]

If the \( n \) concentrated forces \( f_C \) are equivalent to a resultant force \( F_C' \) again, the relationship between \( F_C' \) and \( f_C \) is:
In the formula:

\[ F_c = \sum_{i=1}^{n} f_i \cos \varphi_i = f_c \sum_{i=1}^{n} \cos \varphi_i \]  

(3)

In the formula:

\[ \varphi_i = \frac{1}{2} + \frac{2i-1}{2n} \alpha \]  

(4)

3.2. Force simulation

In this paper ANSYS Workbench is used for simulation. There is a ring and fin-ray structure in the simulation. The rigid part of the fin-ray structure is defined as ABS plastic, and the soft part is defined as the "rubber2" material set in the library. Fix the ring and the bottom right corner of the fin-ray structure, then apply a torque which is 30.75N*mm to the bottom of fin-ray structure, and the boundary result of von-Mises stress simulation is obtained and shown in Figure 6.

It can be seen from the result in Fig. 6(a) that each node has a stress distribution in the contact area, and there are obviously distributed loads of four concentrated areas. Consider using n equivalent models of concentrated forces to describe the force. Figure 6 (b) shows the enveloping process of the fin-ray structure. During the whole process, the stress concentration area is gradually converted from one to four, and the number of concentrated areas corresponds to the number of rigid links contained in the contact area.

The node data of the ANSYS stress result has been derived and further analyzed. There are 175 evenly distributed nodes on the whole ring, and about 40 nodes in the contact area. The concentrated force from distribution\( f_i \) in a single area is:

\[ f_i = t \cdot h \cdot \sum \sigma \]  

(5)

In this formula, \( t \) is 15mm represented of the thickness of the ring, \( h \) is the distance between two nodes, which is calculated from the circumference of the ring divided by the number of nodes, and \( \sigma \) is the stress value derived from each node. The result of \( f \) derived from formula (5) is:

\[ f = [0.4623N, 0.6493N, 0.5852N, 0.5388N] \]

4. Experiment

4.1. Platform

In order to verify the performance of soft pinching, a prototype is made as the platform of experiment.

The experimental platform is shown in Figure 7. It mainly consists of soft under-actuated hands, laptops, Arduino system, stepper motor drives and DC power. The total weight of the hand is about 800g, the height is 27cm, and the diameter of the base circle at the bottom is 15cm. In addition to the pin, bolt, sliding bearing, guide rail, slider and other standard parts, the mechanical structure is mainly made of ABS plastic through 3D printing, and the fin structure is made of rubber through 3D printing. In order to increase the friction of the contacted area, the surface of the three fingers is affixed with a
layer of vulcanized rubber with long grain. Arduino is to control three stepper motors and a servo in the palm structure.

4.2. Contrast experiment

To verify the performance of the soft pinching based on the fin-ray structure compared to the conventional under-actuated linkage mechanism, several sets of contrast experiments were performed, as shown in Fig. 8. The objects in the experiment included small balls with different diameters, pens, long blocks and cylinders whose diameter is 3cm. Fig. 8(a) used the soft pinching to hold objects, and Fig. 8(b) used parallel pinching. Both pinching modes successfully hold things.

However, in order to compare the difference between the two levels of stability, in this experiment the heavy suspension is hanged to test the performance. As shown in Fig. 9(a), after holding the objects stably, the hand is placed completely laterally, and the water bottle is tied by the string to suspend on the object, and the weight of the suspension is increased by adding water into the bottle. Add 10g every time until the object falls down. In this way, the maximum lateral interference force that the hand can suffer is tested; Fig. 9(b) placed the hand upside-down to test the maximum upward interference that can be suffered.
Fig. 10 shows the contrast experiment results. Based on them, the following conclusions can be derived:
1) In terms of anti-interference ability toward lateral direction, the fin-ray structure has 0–36% improvement over than the conventional under-actuated mechanism. The better the soft fin-ray structure envelops objects, the performance improves much more. When the 28mm diameter wooden ball and the 30mm diameter cylinder are pinched, the performance is improved by 36%.
2) The anti-interference ability toward top direction is obviously improved. For 40mm wooden balls, the maximum suspension weight of the fin-ray structure is 140g, but the result of compared structure is only 40g. Moreover the performance is improved by 250%. For the 19mm wooden ball, due to the better enveloping effect, the top suspension weight increases to 380g and the performance increases by 280%.

5. Conclusion
In this paper, a new soft under-actuated hand was designed based on the under-actuated mechanism and fin-ray structure. It could hold different objects using two gripping modes. The force analysis and simulation in ANSYS were used to verify the newly added fin-ray structure. The contrast experiment shows that soft fin-ray structure can make the pinching stress distribution uniform and also has a good performance of pinching small objects.

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