Design and Analysis of a Robot Hand Based on the Combination of Continuous Flexible Finger and Rigid Tendon Drive Fingers

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Abstract. As the most important end-effector of the robot, the robot hand determines the performance of the robot to a certain extent. Therefore, the robot hand often needs high degree of flexibility and large grasping force to complete complex and diverse tasks. However, most of the existing robot hands are usually difficult to meet the above two requirements. Aiming at this problem, a dexterous robot hand driven by tendon ropes was designed in this paper. Its thumb is a continuum flexible finger with a nickel-titanium alloy wire as the center rod, and the remaining four fingers are tendon-driven rigid fingers. This design allows the thumb to adapt to objects of various shapes, so that the entire robot hand is extremely flexible, and the rigid structure of the four fingers can provide an enough grasping force for the robot hand. In this paper, the robot hand was mechanically designed and simulated by simulation software to ensure the reliability of the design. The workspaces of fingers were calculated by Matlab through the established DH coordinate system and kinematics model of the robot fingers. In this paper, a physical model of the robot hand was made through 3D printing technology, and thin-film pressure sensors are installed at the end of the fingers to measure the grasping force in real time. Finally, various shapes of objects were selected for the grasping operation, which verified the flexibility and enough grasping force of the robot hand.

Keywords: Robot hand, continuum robot, flexibility, gripping force.

1. Introduction
Robots are particularly important in the fourth industrial revolution dominated by intelligent manufacturing. In particular, the continuous iteration of robotic robot hands enables robots to replace human hands to a certain extent and are widely used in various fields. However, in some unstructured environments, the tasks performed by robots are more complicated, and most of the existing robot hands are difficult to play a better role, especially taking into account flexibility and grasping force.

The existing robot hands are mainly divided into two categories, namely rigid robot hands and flexible robot hands. The DLR-HIT II [1] [2] robot hand jointly developed by Harbin Institute of Technology and the German Aerospace Agency is a relatively classic rigid robot hand. The fingertips torque of the robot hand is large and the operation accuracy is high. However, the robot hand also has problems such as insufficient flexibility, complex control, and high cost. It is difficult to perform well
when performing grasping tasks in a complex environment. In addition, rigid robot hands such as Gifu-II and DLR-I [3] [4] also have this kind of common problems. Zhao and others from Cornell University invented a flexible robotic hand that uses the flexible material and tendon drive, and this robotic hand can estimate the size of the grasping force by the degree of bending of the optical fiber. This kind of robot hand is relatively soft, can adapt to the shape of different objects, and has a certain degree of flexibility. However, it also has some common problems of flexible robot hands such as small grasping force and poor control accuracy.

Aiming at some of the problems of the existing classic robot hands, this paper introduces a kind of robot hand based on the combination of continuum flexible fingers [5] and tendon-driven rigid fingers. The thumb of the robot hand adopts a continuum design, which has more degrees of freedom than the traditional linkage design. This gives it the same flexibility as a human hand. The other four-finger mechanism is designed with a tendon-driven linkage, which can provide an enough grasping force. The cooperation of the two types of fingers can make the whole hand both flexible and with enough grasping force, thereby ensure that the robot hand can complete more complex grasping tasks.

1. The mechanical design of the robot hand includes flexible thumb joints and multi-link four fingers, the angle and arc of the finger palm. And the simulation design of the control system. [6] [7]
2. Establish the kinematics model of the five fingers. According to the established kinematics model and static model, the manipulator is simulated and calculated under different gestures to solve the work space. [8] [9]
3. Create a solid model through 3D printing technology, conduct a simulation experiment of human hand movements, and compare with the simulation results. [10]
4. Draw conclusions.

2. Mechanical Design
The five fingers of a classic robot hand mostly use a connecting rod structure, and its degree of freedom limits the workspace of the robot fingers and also affects the grasping flexibility of the hand. The degree of flexibility of the human hand is mainly depends on the flexibility of the thumb, especially the root of the thumb, which can rotate freely like a ball joint. This degree of freedom of rotation of the thumb and the degree of freedom of bending of the other four fingers can be used to grasp objects of various shapes. Therefore, if the thumb of the robot hand has the same degree of freedom, it can be as flexible as a human hand. According to this research idea, we designed a robot hand based on the combination of continuum flexible finger and rigid tendon-driven fingers, so that the five fingers of the entire robot hand can have a degree of freedom similar to that of a human hand, thereby being more flexible.

The overall structure of the robot hand in this paper is similar to the human hand, as shown in Figure 1. Among them, the index finger, middle finger, ring finger and little finger adopt the same structural design. The three knuckles of each finger are rigid structures, and by stretching the tendon rope fixed at one end to the fingertip, each knuckle can be rotated around the axis, So as to achieve the bending of the entire finger. The thumb adopts a continuum structure supported by an elastic central skeleton and multiple disks disks arranged in parallel. The bending of the fingers is also driven by tendons. The thumb structure of the robot hand is shown in Figure 1.
The thumb has a **Nitinol** wire with a diameter of 0.5mm as the central skeleton, which plays a role of support and rebound. In the skeleton, a total of 15 small disks are inserted, each of which has a thickness of 3mm and a diameter of 20mm. On each disk, there are eight holes with a diameter of 1.5mm arranged in a circle, and the driving tendon is inserted into each disk through these holes. In order to keep the center of each disk at a fixed distance, a joint ball is inserted between two adjacent disks so that the disk does not move when the fingers are bent. Among them, in order to ensure that the fingers can achieve a better bending effect, 7 joint balls with a diameter of 3mm are penetrated near the base of the finger, and 7 joint balls with a diameter of 5mm are penetrated near the fingertip. The thumb of the robot hand is driven by tendon ropes. Eight tendon ropes are inserted into the eight holes on the disk, and every two adjacent tendon ropes are connected to one end of the steering wheel. When working, the steering gear drives the ropes in different disk holes, which can cause the elastic skeleton to bend in the corresponding direction, thereby controlling the movement of the thumb. The other four fingers of the robot hand except the thumb are all connected rod structures, and the structure is shown on the left side of Figure 1. The three knuckles of each finger are connected by pins. The back of the finger is inserted with Nitinol wire as a rebound device, and the front part is inserted with a driving tendon rope to connect the steering gear.

All the joints, palms and arms of the robot hand are printed with 3D printing material PLA. The final assembly effect is shown in Figure 1 (middle).

In this paper, a robot hand control system is made based on Arduino uno. The control circuit of the robot hand is shown in Figure 2. The X port of joystick 1 controls the steering gear that moves the thumb up and down; the Y port of joystick 1 controls the steering gear that moves the thumb left and right; the joystick 2 controls the index finger steering gear; Stick 3 controls the middle finger servo; joystick 4 controls the ring finger servo; joystick 5 controls the little finger servo. When controlling the robot hand, it sends a direction signal by manipulating the joystick. After receiving the signal, Arduino uno recognizes the received signal through the program, controls the corresponding steering gear to rotate and pulls the corresponding rope, so as to achieve the purpose of bending the fingers.
Figure 2. The control circuit of the robot hand

Pressure sensors are installed on the belly of each finger, which can measure the grasping force generated when the finger grasps objects. When the finger touches the grasped object, the pressure sensor on the fingertip returns the reaction force signal received to Arduino uno. When the reaction force reaches the set limit value, Arduino uno will send a signal to prohibit the steering gear from continuing to rotate in this direction.

3. Work Space
In order to analyze the finger motion state of the robot hand and the working area of the finger end, this paper studies the workspace of the robot finger. By writing a program in MATLAB and performing calculations, the workspace of the two fingers of the robot hand is obtained.

For the four rigid connecting rod fingers, the parameters are shown in Table 1.

Table 1. The length of each joint of multi-link finger

| Multi-link fingers | Finger root | Middle finger | Knuckles | Relative range of motion between joints |
|--------------------|-------------|---------------|----------|---------------------------------------|
|                    | 43mm        | 38mm          | 35mm     | 90°                                   |
Figure 3. Multi-link fingers

Through matlab calculation, it can be seen that the traditional multi-link fingers can only rotate in a plane, and the three-dimensional working space is only a plane, as shown in Figure 3.

In order to compare the difference between the working spaces of the two fingers, the same finger length parameters are set in the model, and the working spaces of the two fingers are shown in Figure 4.

Table 2. Flexible finger parameters

| Flexible joint finger | 3mm disk | 3mm joint | 5mm joint | Relative range of motion between joints |
|-----------------------|----------|-----------|-----------|-----------------------------------------|
|                       | 15       | 7         |           | 90°                                     |
After calculation, as shown in Figure 5 (left), the workspace of flexible finger is a three-dimensional space, and it is much larger than that of multi-link fingers.

Using the hold on function of the robot toolbox to retain images for comparison, as shown in the comparison diagram of Figure 5(right), it is further confirmed that the workspace of flexible fingers is much larger than multi-link fingers.
Through the analysis module of the 3D software, the workspace can be compared more intuitively. It can be seen from Figure 6 that the design of the flexible finger thumb effectively improves the working space of the robot hand.

4. Experiment

According to the analysis of the workspace of the robot fingers in the previous section, the workspace of the robot hand with the flexible continuum structure of the joint thumb is analyzed and solved by the simulation software. It is found that the workspace is greatly improved compared to the rigid link finger. Various types of fingers can cooperate with each other to achieve tasks that cannot be completed by a robot hand which only has rigid link fingers.

In order to further determine the feasibility of the grasping flexibility design of the robot hand described in this article, in addition to software simulation, this article also carried out a grasping experiment test with the simulated human hand posture by grasping objects of different shapes. By controlling the robot hand to make a variety of enduring common complex and common operation gesture simulations, the robot hand can achieve stable grasping of objects of different shapes. It is verified that the feasibility experiment of the robot hand design in this paper is confirmed. The physical test is shown in Figure 6, where eight kinds of gesture tests that are difficult to complete by conventional multi-rigid link robot hands are entered.

As shown in Figure 6,

(a) is an open gesture, showing the initial state of the five fingers. (b) is the scissors hand gesture, showing the most common movements of the simulated human hand. (c) is an ok gesture, showing that the thumb can be pinched with the index finger. (d) In order to grasp the handshake, show that the five fingers can grasp the sphere. (e) To hold the stick gesture, show that the fingers can hold the stick-like object. (f) is a pinching gesture, showing the gripping force of the thumb and index finger. (g) To show the driving force of the thumb by pressing the grace gesture. (h) is to pinch objects to show the coordination of the five fingers.

Through a variety of human hand motion simulation experiments, the results show that the robot hand with flexible continuum joint thumb has high flexibility, and its grasping performance is greatly improved compared with the rigid link robot hand. The actual workspace and the software simulation results are similar.
5. Conclusion
In this paper, a novel robot hand with a flexible thumb and four rigid multi-link fingers was designed. In order to ensuring the grasping space of these five fingers, the working space of these fingers are analyzed. According to the work space of fingers, the flexible thumb is able to improve the ability to grasp objects. Then, the physical model of this robot hand was made by using 3D printing technology. Finally, a experiment was carried out, and the experiment shows that this robot hand is able to achieve different grasping gesture and grasps different kinds of objects.

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