Structural design and kinematics analysis of SHU-hand II humanoid robotic hand

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Abstract. A five-finger humanoid robotic hand is designed based on the structure of human hand. It has five fingers, 16 degrees of freedom. In the theoretical research of robotic hand, the kinematic is established by homogeneous transformation matrix, and then the motion trajectory of five fingers is obtained. The gesture and grasping experiment are carried out, it shows that more than ten kinds of behaviour can be achieved by robotic hands, such as pinching and holding etc. The robotic hand is installed in different robot platforms to verify that it has a wide range and good ability of grasping in different environments.

1. Introduction
Design of robotic hand needs to determine the degree of freedom and the way of using the driver. The number of joints is determined by the freedom, the way of using the driver affects the accuracy and complexity of finger’s rotation. According to the layout of the driver, it is divided into built-in driver and external driver [1], and according to the choice of driving mode, it is divided into full drive and under-actuated [2]. Robonaut hand [3] has 5 fingers with 14 degrees of freedom, and 14 drivers are placed in the forearm as external driver. The hand can reach a very accurate position. But at the same time, the complexity of the system increases. Fast, accurate and reliable grasp can be achieved when use under-actuated robotic hand, and the structure can be also lightweight. DHR-HIT HAND II [4], has a total of 15 degrees of freedom with less driver. Due to the reduced number of drivers, the structure of the hand has been simplified, the complexity of the entire system decreases while the controllability of system increases.

The research and development of robotic hand is the process of mechatronics [5], so we need to study the structure of robotic hand to cooperate with the motion control. UB-hand IV [6-7], developed by University of Bologna, with integrated pin joint, can bear multiple bending rotations and complete a variety of grasping behavior. ISR-softhand [8] has rigid material with phalanges, and plastic material with joint. The drivers are placed in the back of the palm, increased the thickness. Shadow Hand, [9] designed by Shadow Hand company, is similar to the human hand. The base of the finger contains two degrees of freedom. The hand uses 40 sets of pneumatic muscle on the forearm as the driving source,
can grasp fragile objects. The Etho-hand [10] uses spherical joints at the thumb to increase the volume of the palm and provides a wide range of complex movements.

This paper designs SHU-hand II five-finger humanoid robotic hand based on the SHU-hand I [11]. The controllability is increased by using underactuated system. The control module is built into the palm to reduce the size. SHU-hand II also reduces the complexity of the structure at the joints and the weight of the fingers, while ensuring a large range and good ability of grasping. The kinematic trajectory of SHU-hand II is obtained by homogeneous transformation matrix. The flexibility and grasping ability of the robotic hand is verified by grasping different objects on the experimental platform. And the better transplant ability is also presented by installing in different robot platform.

2. Structural design of SHU-hand II

SHU-hand I robot consists of three fingers and has some limitations to complete some grasping function. Based on it, this paper designs SHU-hand II humanoid robotic hand. The ratio of the size of SHU-hand II to the manpower is 1.1:1, the specific size shown in Figure 1. SHU-hand II consists of a palm and five fingers. The thumb has four degrees of freedom and the remaining four fingers have three degrees of freedom. Each of the parts is made of ABS material by rapid prototyping, the total mass is about 1kg.

![Figure 1. SHU-II hand](image1)

![Figure 2. (a) Simple model of finger placed (b) The model of phalanges](image2)

The designs of finger refer to the structure of human finger. The human finger is similar to the trapezoidal side. The finger is divided into four parts, the basal phalanges, the proximal phalanges, the intermediate phalanges and the distal phalanges. It contains three rotational joints. Actually, the joint can be equivalent to the rotation axis. There are many types of joints, which can be embodied as a pulley or a piece of flexible material. In order to reduce the weight of SHU-hand II and reduce the complexity of the fingers, the robot uses a wire rope to drive. The finger model shown in Figure 2(a).

![Figure 3. (a) The finger models. (b) The Explosion diagram of finger model](image3)

![Figure 4. The driven structure of finger.](image4)
In order to reduce the influence of the lateral load on the finger, the model is modified. As shown in Figure 2(b), baffles are extended at both ends of the phalanges to prevent lateral displacement of the finger. In order to achieve a supple bending of the finger, the spring with the same length and width as the finger is mounted on the back of the finger, which not only increases the elasticity of the joints, but also connects the different phalanges tightly. It can bring great convenience. At the same time, the basal phalanges, the proximal phalanges, the intermediate phalanges, and the distal phalanges have been modified in appearance. The final model is shown in Figure 3(a). In this model, as shown in Figure 3(b), the spring is pressed on the phalanges, each phalanx is corresponding to a phalanges cover. These parts are connected together to form a complete finger structure.

SHU-hand II uses six DC motors to control the movement of fingers. Five of the motors drive the flexion of the fingers through controlling the contraction of the wire rope, as shown in Figure 4. Another motor drives the inside and outside of the thumb. The design of the palm is shown in Fig. 5, The driver has a built-in arrangement, and the control module is also placed inside of the palm. Therefore, SHU-hand II has a high degree of integration and can be easily installed in different robot platforms as required.

3. Experiment and application of SHU-hand II

3.1. Kinematic model

The kinematic analysis of the SHU-hand II is to find the trajectory of the end point of the fingers. As shown in Figure 6. (a), set root of the thumb as the palm coordinate system $x_0y_0z_0$, set the finger coordinate system at the phalanges. So, we can get the position of end point of the fingers relative to the palm coordinate system through homogeneous transformation.
3.1.1. Four-finger kinematics analysis. The index finger, middle finger, ring finger, and little finger adopt a modular design. The structure of the four fingers is similar, can achieve the same grasping function. Take the index finger as an example, establish the index finger coordinate system as shown in Figure 6. (b), where x21o21y21 is the base coordinate system of the index finger.

The phalanges of finger are connected by spring. During the finger grasping process, the spring will bend, and the adjacent phalanges will move a distance from each other. Therefore, the finger coordinate system is shown in Figure 7 when finger is moving.

As can be seen from Figure 7, the spring will bend in the movement of the finger, the phalanges movement distance can be equivalent to the tangent length of the spring plate arc. The homogeneous transformation matrix of adjacent phalanges is:

\[
{^{i-1}T_j} = \begin{bmatrix}
c\theta_{i-2} & -s\theta_{i-2} & 0 & l_{i-2} + (l_{i-2} + a_{i-1})c\theta_{i-2} \\
s\theta_{i-2} & c\theta_{i-2} & 0 & (l_{i-2} + a_{i-1})s\theta_{i-2} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[i = 3, 4, 5; \ j = 2, 3, 4, 5\] (1)

In the formula, \(^{i-1}T_j\) represents the homogeneous transformation matrix of j-th finger's phalanges end movement point, where from the i coordinate system to the i-1 coordinate system. And ai (i=3, 4, 5) is the length of the proximal phalanges, the intermediate phalanges and the distal phalanges, i is the sequential numbers of the finger coordinate system, j represent the sequential numbers of four fingers.

According to the phalanges bending movement, we can get

\[l_{i-2} = r_{i-2}\tan \frac{\theta_{i-2}}{2} \quad i = 3, 4, 5\] (2)

In the formula, \(l_{i-2}\) is the tangent length of the curved arc of spring, \(r_{i-2}\) is the radius of joint, and \(\theta_{i-2}\) is the rotation angle of joint.

The basal phalanges of the four fingers are fixed, so the homogeneous transformation matrix at the base of the finger is

\[
{^{i}T_j} = \begin{bmatrix}1 & 0 & 0 & a_i \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad j = 2, 3, 4, 5
\] (3)

where \(a_1\) is the length of the basal phalanx.

The Pij at the end point of the phalanges is \(P_{ij} = [0 \ 0 \ 0 \ 1]^T\) in its own coordinate system. The coordinates of Pij in the finger’ base coordinate system xjyjzj1 is

\[
P_{ij} = {^{i}T_j} \cdot {^{i-1}T_j} \cdot \ldots \cdot {^{2}T_j} \cdot P_{ij} \quad i = 2, 3, 4, 5; \ j=2,3,4,5
\] (4)

The homogeneous transformation matrix of the finger base coordinate system to the palm coordinate system is
\[
{^0}_1T_j = \begin{bmatrix}
1 & 0 & 0 & x_j \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & z_j \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\( j = 2, 3, 4, 5 \) (5)

In the formula, \( x_j \) and \( z_j \) are the coordinates of the point represented by the finger base coordinate system in the palm coordinate system. According to equations (1), (2), (3), (4), and (5), the position of end point \( P_{ij} \) in the palm coordinate system \( x_0y_0z_0 \) can be obtained

\[
P_{ij}^0 = {^0}_1T_j \cdot P_{ij}^1
\]

(6)

3.2. Kinematics simulation

According to the formula, the position of end point can be obtained. The trajectory of the fingertip can be solved. Table 1 shows the phalanges length of each finger. The finger’s movement trajectory is drowning in the three-dimensional space. The bending range of each phalanges is \( 0^\circ \sim 60^\circ \). At the same time, the thumb swings inside and outside the \( z \) axis, the movement range is \( 0^\circ \sim 90^\circ \). As shown in Figure 8, the black part of the figure is the bending range of the distal phalanges, the green part is the bending range of the middle phalanges, the blue part is the bending range of the proximal phalanges.

**Table 1.** Finger’s parameters

| Finger      | \( A_1 \) (mm) | \( A_2 \) (mm) | \( A_3 \) (mm) | \( A_4 \) (mm) |
|-------------|----------------|----------------|----------------|----------------|
| Forefinger  | 25             | 31             | 27             | 20             |
| Middle finger | 25            | 31             | 27             | 23             |
| Ring finger  | 25             | 31             | 27             | 20             |
| Little finger | 25            | 28             | 22             | 20             |
| Thumb       | \( \backslash \) | 28             | 22             | 20             |

![Figure 8](image1.png)

**Figure 8.** The motion trajectory of five fingers.

On the YOZ plane, as shown in Figure 9. The upper part of the figure shows the motion range of the four fingers, and the lower part shows the motion area of the thumb. There is an overlap between the thumb and other four fingers. It shows that the thumb and the other four fingers can cooperate together to achieve the pinch function. The envelope surface is formed between the fingers, so that the object can

![Figure 9](image2.png)

**Figure 9.** The motion trajectory of five fingers in YOZ.
be grasped. As we can see from Figure 9, the bending area of the four fingers is in the range of 0–80mm, and the bending area of the thumb is 0~125mm. In space, the total distance between the four fingers is about 100mm. In summary, SHU-hand II can grasp objects with a wide range of dimensions.

4. Experiment and application of SHU-hand II

4.1. Pose experiment
SHU-hand II can complete some common gestures when the robotic hand is in no load, as shown in Figure 10.

![Figure 10. The gestures of SHU-hand II in no load.](image)

SHU-hand II can achieve "1", "2", "3", "6", "ok" and other postures. By changing the angle of the thumb and the bending angle of the five fingers, each finger can flexibly cooperate to show common gestures. It can also be seen from Fig 11. that the thumb has a large range of rotation, so it is possible to grasp larger objects in space.

4.2. Grasping experiment
SHU-hand II can achieve the behavior of pinching, gripping, and clipping by the cooperation between the five fingers. Table 2. shows the parameters of objects which this paper used in the experiment. The specific grasping results are shown in Figure 11.

| Object     | Weight (g) | Size (mm)     |
|------------|------------|---------------|
| Pen        | 16         | D=8.7, L=131.8|
| Card       | 12         | L=85.5, W=53.9, H=0.9 |
| Apple      | 180        | D=84.4        |
| Banana     | 224        | L=186.6       |
| Small Box  | 60         | L=90, W=62.4, H=19.2 |
| Middle Box | 152        | L=108.5, W=81.1, H=63.5 |
| Small Bottle | 340     | D=66, L=116 |
| Disposable Cup | 84     | D=60, L=86 |

In this table, D denotes the diameter of the object, L denotes the length of the object, W denotes the width of the object, and H denotes the height of the object.

When the robotic hand grasps a cylinder with a small diameter or a thin card, as shown in Figure 11. (a), 11. (b), the thumb can be used with the index finger or middle finger to pinch the object. When grasping the box, as shown in Figures 11. (c) and 11. (d), for the smaller box, the robotic hand can use three fingers for clipping. For the larger box, the thumb can fit four fingers to clip. When grasping a spherical object, as shown in Fig 11. (e), five fingers act on the surface of the sphere to form a force closure, and the hand can grasp the sphere by gripping. When Grasping the longer cylinder, as shown in Figures 11. (f) and 11. (g), the robotic hand also uses the gripping mode. SHU-hand II can pick up the water cup by gripping, as shown in Figure 11. (h).
Experimental results show that when the object is grasped, the hand shows different postures according to the size of the object. And it reflects a good self-adaptation. In the experiment, SHU-hand II grasping the minimum thickness of the object is 0.9 mm, and the diameter of the cylinder taken from 8.7 mm to 66 mm, the weight of the grasped object can exceed 1 kg. The experimental results are in good agreement with the kinematics analysis of the robotic hand. It is further confirmed that SHU-hand II can achieve gripping, pinching, clipping and other grasping functions, and has good Stability and adaptability.

4.3. Application

The experiment results of the robotic hand have proved that it has a stable and flexible grasping capability. The control module is placed in the palm, so the robotic hand can be connected with the robot platform only with a flange of suitable size. The design of flange is shown in Figure 12. SHU-hand II is placed on the UR arm to complete the fruit sorting function. As shown in Fig 13, during the fruit sorting process, when a specific colour of fruit is detected, the UR arm will move to a suitable position, SHU-hand II grasps the fruit steadily. During the movement of the UR arm above the bamboo basket, the fruit does not shake or fall off until SHU-hand II releases it. This proves the stability of grasping of SHU-hand II.

Figure 11. Grasping object with SHU-hand II.

Figure 12. The connecting flange.

Figure 13. Fruit sorting with SHU-hand II.

Figure 14. Pouring water with SHU-hand II.

Figure 14. shows the use of SHU-hand II for installing on Baxter robot. The two robotic hands cooperate to complete the pouring behaviour. During the experiment, the left robotic hand grips the cup and raises it to about 80 mm. The right robotic hand holds the water bottle and raises it to the top of the
cup. Then the right robotic hand began to tilt, complete the pouring behaviour. SHU-hand II grasps two objects of different sizes, materials and weights through self-adaptiveness, and can maintain the stability of the grasp.

Through the use of SHU-hand II on two types of robot platform, the stability of grasping of SHU-hand II is further verified. It is also proved that on different robot platforms, SHU-hand II can show the self-adaptive grasp.

5. Conclusion
This paper designs a new type of five-finger robotic hand with 16 degrees of freedom. It can achieve 10 kinds of behaviours such as clipping, pinching and gripping. A kinematics model was established to obtain the position of the finger's end point, the motion trajectory and grasping space of robotic hand are solved. The experiment verifies the flexibility and stability of grasping of SHU-hand II. In the following study, four fingers can add one more degree of freedom, in order to achieve the function of swing.

Acknowledgements
This work is supported by Municipal Science and Technology Commission of Shanghai (No. 15411953500).

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