Design and Analysis of Underactuated Humanoid Robotic Hand Based on Slip Block-Cam Mechanism

Shengqi Tan, Wenzeng Zhang, Qiang Chen, Dong Du

Abstract—Compared with traditional dexterous humanoid robotic hands, underactuated robotic hands have the advantages of self-adaptive grasp and easy real-time control. In this paper, the development of a novel underactuated robotic hand is presented. This hand has five fingers and through using underactuation, the self-adaptability of each finger is achieved. This underactuated humanoid robotic hand can accomplish complicated self-adaptive grasp without high demand for real-time control system. In the first place, the design of a two degree-of-freedom underactuated finger is given. Then the parameters affecting the rotary angle and grasp force of the finger are analyzed and optimized. Finally, taking one finger as a module, the entire humanoid robotic hand is designed. This robotic hand is similar to human hand on appearance and size. It has many good merits such as good self-adaptability, compactness, easy real-time control, small volume and light weight.

I. INTRODUCTION

At present in the research field of robot technology, robotic hands which play an important role in human robot are being more and more emphasized and the goal to create a robotic hand with high personification replacing human hand is much anticipated. However, dexterous robotic hands cannot accomplish complicated work self-adaptively because they are not capable of self-adapting the shapes and sizes of different objects. And also the robotic hands need to be designed more DOFs to elevate their personification, while the number of actuators which increases the difficulty of real-time control correspondingly. And increasing the number of actuators means increasing the volume and weight of the hand which is hard to solve at present. But the underactuated hands which have fewer actuators than DOFs can grasp objects without complex control and sensors. They can increase the stability of grasp, reduce the number of actuators and the difficulty of control, and reach a wide range of grasp, etc. So they enable to actuate more DOFs with fewer actuators and simultaneously to grasp objects with different sizes and shapes self-adaptively. Naturally underactuated robotic hands become an important research direction in humanoid hands currently. The personification degree of the robotic hands is an important performance index, reflecting in following three respects: first, the distribution and movement relations of each finger and the palm need to be similar to human hand; second, the grasp force of the hands during the grasp processing need to reach a certain requirement; finally, the sizes of the fingers and palm need to be similar to the statistical sizes of human hands.

Many institutes and researchers have made great achievements in this field in recent years, such as Laval University [1-2] (Birglen, et al) in Canada, TUAT [4] (Tokyo University of Agriculture and Technology, Fukaya, et al) in Japan, Harvard [15] (Dollar, et al) in USA, and HIT [3] (Harbin Institute of Technology, Liu, et al), BUAA [12] (Beijing University of Aeronautics and Astronautics, Guo, et al), Tsinghua University [4-5] (Zhang, et al) in China, etc. And former designs include: the Shadow dexterous hand [16], TUM hand [10], Utah/MIT Hand [17], the DLR-HIT Hand [5], the SDM hand [15], the TH series hands [9-10], and etc.

The SARAH hand [1-2] developed by Canadian MD ROBOTICS Corporation and Laval University enables to realize to drive 10 DOFs with only 2 actuators, which showing good effect of underactuation. The hand is composed of underactuated fingers with transmission mechanisms founded on either linkages or tendons and pulleys.


The underactuated fingers can be divided into two styles: direct and indirect styles. In the direct style underactuated finger, the actuator is connected to all joints by special mechanisms; in the indirect style underactuated finger, the actuator is connected to the closest joint and not the other joints directly, the torque of actuator is only connected indirectly to the other joints by the phalanges. TH-2R [4] Hand belongs to an indirect style underactuation which benefits from the gear-rack transmission mechanism. TH-3R [5] Hand belongs to a direct style, which uses the mechanism of gear-rack. Here, the “R” means rack in short.

This paper presents a humanoid robotic hand with indirect style underactuated fingers. The hand described is named TH-2C Hand. Here, the “C” means cam in short. First, the design of a 2 DOFs finger is proposed. Then, the parameters related to the movement and forces of the grasp processing are analyzed. Finally, the humanoid robotic hand applied with
the finger discussed before is designed.

II. THE NOVEL UNDERACTUATED FINGER

A. Principle and Structure of the Underactuated Finger

A novel underactuated finger based on the slip block-cam mechanism is designed. The finger achieves the effect of underactuation through transmitting the slip block’s small movement to the cam’s big rotary angle. Its detailed structure is shown in Fig. 1.

![Fig. 1. The underactuated finger](image)

This underactuated finger is composed of three parts: the 1st Segment, the 2nd Segment and the underactuated mechanism. The underactuated mechanism includes a slip block, a cam, a spring, a block, a torsional spring, the 2nd segment shaft and a cam shaft. There is no actuator appearing in the underactuated mechanism. The finger’s driven forces rely on the contact forces produced by grasped objects under the motion of other active fingers and joints. Slip block is embedded in the 1st segment and can only move towards the horizontal direction in Fig. 1. The cam is pushed to rotate around the cam shaft by the slip block. Spring and torsional spring make the cam and slip block move back to their initial positions. This processing is in contrary to the grasp processing.

This underactuated finger is demonstrated to achieve good selfadaptability to the size and shape of the grasped object well. When the object is too small or has odd shape, the slip block cannot contact well with the object, the 2nd segment and the other fingers can be used to pinch this object stably.

![Fig. 2. Sketch map of the principle of the underactuated finger](image)

III. ANALYSIS AND OPTIMIZATION OF THE UNDERACTUATED FINGER

A. Movement Analysis of the Underactuated Finger

Fig. 3 shows the dimensional parameters of each part of the underactuated finger. $O_1$ and $O_2$ are the rotary centre of the cam shaft and the 2nd segment shaft respectively. Point $A$ is the contact point between the slip block and the cam. Let $O_1O_2=L$.

- $S$: coordinates in $X$ direction of point $A$, mm;
- $h$: coordinates in $Y$ direction of point $A$, mm;
- $R$: distances between point $A$ and $O_1$, mm;
- $\alpha$: angle between line $AO_1$ and $X$ axis, rad;
- $\delta$: angle between line $AO_2$ and $O_1O_2$, rad;
- $\Delta\alpha$: the rotary angle of the cam, rad;
- $\Delta\beta$: the rotary angle of the 2nd segment, rad;
- $\Delta S$: the displacement of the slip block, mm.

According to the geometrical relationship, the equation between the horizontal movement of the slip block and the rotary angle of the 1st segment is calculated as follows:
\[ \Delta \alpha = \arctan \frac{h}{s} - \arctan \frac{h}{s} \]  (1)

Then the rotary angle of the 2nd segment is calculated:

(1) When \( \Delta \alpha \leq \delta (\delta = 14') \)

\[ \Delta \beta = 39' - \arcsin \frac{R \sin (\delta - \Delta \alpha)}{\sqrt{R^2 + L^2 - 2RL \cos (\delta - \Delta \alpha)}} \]  (2)

(2) When \( \Delta \alpha > \delta (\delta = 14') \), then

\[ \Delta \beta = \arccos \frac{(R+L) - RL \cos \delta + \cos (\Delta \alpha - \delta)}{\sqrt{R^2 + L^2 - 2RL \cos (\Delta \alpha - \delta)}} \]  (3)

As the instrument of precise grasp, the grasp processing of the underactuated finger need to be stable and easy to real-time control and the movement should have good linearity. The main affecting factors are the dimensions of the geometrical parameters of the mechanism. The analysis of the movement of the finger is shown as follows:

According to the initial sizes of the parameters, let \( h=6 \text{mm}, \ s=8 \text{mm}, \ R=13 \text{mm}, \ L=16.5 \text{mm}, \ \alpha=69^\circ, \ \delta=14^\circ \). Fig. 4a and 4b show the curves of \( \Delta \alpha=f (\Delta s) \) and \( \Delta \beta=f (\Delta \alpha) \) respectively.

The figures in the Fig. 4 show the good linearity of the movement. In details, small movement of the slip block can cause big rotary angle of the 2nd segment, the effect of underactuation is evident. So it can be deduced that the grasp processing is stable and the gesture control is easy to attain.

**B. Force Analysis of the Underactuated Finger**

Fig. 5 shows the force analysis of the underactuated finger when it grasps an object.

- \( O, O_1 \) and \( O_2 \) is the centre of the base shaft, the cam shaft and the 2nd segment shaft respectively. \( M \) is the contact point between the 1st segment and the object. \( N \) is the contact point between the 2nd segment and the object. \( O \) is the rotary centre.
- \( f_1 \) - the grasp force of the 1st segment to the object and its magnitude equals to the force of the object against the 1st segment, N;
- \( f_2 \) - the grasp force of the 2nd segment to the object and its magnitude equals to the force of the object against the 2nd segment, N.
- \( L_0 \) - distances between points \( O \) and \( O_2 \), mm;
- \( H_1 \) - the arm of force \( f_1 \) with regard to the rotary centre of \( O \), mm;
- \( H_2 \) - the arm of force \( f_2 \) with regard to the rotary centre of \( O \), mm;
- \( r_2 \) - the arm of force \( f_2 \) with regard to the rotary centre of \( O_2 \), mm;
- \( \theta \) - rotary angle of the 1st segment, rad;
- \( \beta \) - rotary angle of the 2nd segment, rad;
- \( M_1 \) - the torque of force \( f_1 \) with regard to point \( O \), Nmm;
- \( M_2 \) - the torque of force \( f_2 \) with regard to point \( O \), Nmm;

According to the force analysis, both torqueses with regard to point \( O \) are calculated as below, i.e.

\[ M_1 = \frac{f_1 \cos \theta}{\cos \alpha} \sqrt{(s - \Delta s)^2 + b^2 \sin (\theta + \Delta \alpha + \arctan \frac{s - \Delta s}{b})} \]  (4)

\[ f_1 R \cos (\delta - \Delta \alpha) + \arcsin \frac{R \sin (\Delta \alpha - \delta)}{\sqrt{R^2 + L^2 - 2RL \cos (\Delta \alpha - \delta)}} \]

\[ M_2 = \frac{f_2 R}{\sqrt{R^2 + L^2 - 2RL \cos (\Delta \alpha - \delta)}} \]  (5)

According to the torque balance of the cam, so

\[ M_1 = M_2 \]  (6)

Let actuator torque name \( M \) and define
The torque balance equation of whole finger with regard to point $O$ is:

$$M = f_1H_1 + f_2H_2$$

(10)

So $f_1$ and $f_2$ is calculated as follows:

$$f_1 = \frac{Mx_2}{x_2H_1 + x_1H_2}$$

$$f_2 = \frac{Mx_1}{x_2H_1 + x_1H_2}$$

(11)

Fig. 5 Force analysis of the underactuated finger

The grasp forces acting on the grasped object reflect the performance of underactuated finger. And the main factors affecting the forces are the sizes of the mechanism and the shape of the object grasped. The analysis and optimization of the forces acted on the object is described as follows:

According to the initial design dimensions, let $h=6\text{mm}$, $s=8\text{mm}$, $R=13\text{mm}$, $L=16.5\text{mm}$, $r_2=17\text{mm}$, $L_0=36.5\text{mm}$, $\alpha=69^\circ$, $\delta=14^\circ$, $\theta=43^\circ$.

1) Firstly, let $r_2$ and $L_0$ act as variables and other parameters as constants, the analysis of $r_2$ and $L_0$ from the perspective of grasp force are showed in Fig. 6a~6b respectively.

The conclusions deduced from the figures above are as follows:

a) With decreasing of $r_2$ and $L_0$, $f_1$ increases.

b) With decreasing of $r_2$ and $L_0$, $f_2$ increases.

In order to increase $f_1$ and $f_2$, the magnitudes of $r_2$ and $L_0$ should below a certain value.

2) Secondly, let $s$ and $h$ act as variables and other parameters as constants, the analysis of $s$ and $h$ from the perspective of grasp force are showed in Fig. 7a~7b respectively.
The conclusions deduced from the figures above are as follows:

a) With increasing of $s$, $f_1$ decreases while $f_2$ increases.
b) With increasing of $h$, $f_1$ and $f_2$ changes a little.

In the whole grasp processing, the increase of grasp forces approach linear with the decrease of $s$ and in order to increase the end grasp force $f_2$, so that the whole grasp forces of the finger approach force-isotropy, the initial magnitude of $s$ should above a certain value.

3) Finally, let $R$ and $L$ act as variables and other parameters as constants, the analysis of $R$ and $L$ from the perspective of grasp forces are showed in Fig. 8a~8b respectively.

The conclusions deduced from the figures above are as follows:

a) In the area of $6 \leq L \leq 12$, $6 \leq R \leq 14$, $f_1$ and $f_2$ may change suddenly which do harm to the grasp processing.
b) In the area of $12 \leq L \leq 16$, $0 < R \leq 6$, with increasing of $L$, $f_1$ and $f_2$ changes a little. With increasing of $R$, $f_1$ increases while $f_2$ decreases.

In order to avoid the break area and increase $f_2$, $R$ and $L$ should be designed well and let $R$ below a certain value.

Until now, the main affecting factors have been analyzed and the design requirement for each parameter has been given. At the same time, the grasp forces achieve ordinary requirement and the grasp processing is stable and of good underactuation effect which can be deduced from the analysis of the movement of the underactuated finger.

### IV. DESIGN OF HUMANOID ROBOTIC HAND

#### A. Design of Multi-joint Underactuated Finger

The design of two joint finger is shown in Fig. 9, and Fig. 10 shows the design of three joint finger. Fig. 11 shows the appearance of the finger with two underactuated joints grasping a cylinder.

Two joint fingers can be designed to act as thumbs in humanoid robot hands and three joint fingers can be designed to act as other four fingers.

#### B. Design of Humanoid Robot Hand

Using the underactuated fingers designed above, the design of the underactuated humanoid hand is shown in Fig.12.
The humanoid hand has similar shape and size with human hand. An actuator is embedded in the palm to drive the thumb to side rotate.

It has 15 DOFs and 6 actuators which all embedded in fingers and palm. The underactuated humanoid robot hand demonstrates to have good selfadaptive grasp ability, low weight and small volume. The grasp forces in each segment are well-proportioned. The whole processing of movement is linear so that to promise the stability and the gesture control during the grasp processing.

V. CONCLUSIONS

This paper proposes the development of design and analysis of a novel underactuated finger using slip block-cam mechanism. A new multi-fingered hand is designed based on the finger. The hand demonstrates to grasp objects with good selfadaptive performance, which applying fewer actuators to drive more DOFs so that decrease the difficulty of real-time control. The linear movement of the grasp processing lays the foundation of precise real-time control.

Future research will focus on optimizing the design of the mechanism to make it more stable and efficient. More humanoid hands with novel mechanisms will be analyzed and optimization.

REFERENCES