清华大学

SRT 结题报告

题目：耦合与主动复合抓取机器人手

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2012 年 9 月 15 日
COSA-UDA Finger: A Novel Coupled and Self-adaptive Under-actuated Finger with Upside-down Actuator

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Abstract—Hands are important parts for humanoid robots, whose structure requires both flexibility and small size. Dexterous hands and under-actuated (UA) hands are designed in two different types, and the coupled and self-adaptive under-actuated (COSA) grasping mode combines the advantages of both the types, which includes the first coupled stage and the second self-adaptive stage. In order to realize the COSA grasping mode, a novel COSA finger with upside-down actuator (COSA-UDA) is proposed in this paper. The COSA-UDA finger utilizes traditional COSA grasping mode, but embeds the actuator into the proximal phalanx in an upside-down way. In this method, the COSA-UDA finger is able to achieve COSA grasping mode easily using a simplified structure, and the finger makes full use of the rest place of phalanx and remains enough space of palm for complicated instruments to be set. In this paper, several traditional fingers designed in COSA mode are compared and analyzed. The design for the structure of COSA-UDA is provided, and a typical COSA-UDA finger is designed in the following discussion. The mechanics module of the finger is established and discussed, and several rules are proposed in order to optimize the size and grasping force of the system. Analyzing results show that the COSA-UDA finger is a feasible optimal design for COSA grasping mode.

I. INTRODUCTION

HANDS are important parts for humanoid robots, whose structure requires elaborately for various functions, such as grasping, carrying and other operations. It is necessary for the hands of robots to have both flexibility and small size. In one hand, the demand of performing complex movements and operations should be met by precise control system. In the other hand, the hands should be smaller and lighter in order to make them more human-like. Dexterous hands have fingers of multiple active joints driven by actuators, capable of grasping objects agilely for complex performance. Typical dexterous hands include Robonaut Hand [1], Utah/MIT Hand [2] and DLR-II Hand [3]. In dexterous hands, however, each joint requires an actuator for its movement, which will surely bring about expensiveness in price and cumbersome in figure and size. Different from dexterous hands in working principles and grasping type, under-actuated (UA) hands, with fingers of more degrees of freedom (DOFs) than the number of actuators, have been designed. Each UA finger with multiple joints is usually actuated by merely one actuator.

As one mode of UA fingers, the coupled UA finger provides a mechanism in which the actuator rotates one of the joints by an angle while all the other joints can rotate by the same angle at the same time. A robot hand consisted of these fingers can perform like a human hand, but cannot adapt to objects of different shape and usually pinches the objects rather than firmly holding them. Examples of hands designed in this way include TBM Hand [4], MANUS-Hand [5] and Southampton Hand [6]. Another mode of UA fingers can be the self-adaptive finger, whose actuator rotates only one of the joints while the others will self-rotate and adjust their movement according to the shape of the objects. The self-adaptive UA hands can adapt to grasping objects of different size and shape and usually hold the objects firmly, but the performance of movement is quite strange as only one joint of the fingers can rotate before touching the objects, which limits the grasping ability as well. The under-actuated hand by HIT [7], ARAH Hand [8], LARM Hand [9] and TH-3R Hand [10] are examples of hands as self-adaptive UA hands.

The coupled and self-adaptive (COSA) finger is the combination of both coupled fingers and self-adaptive ones. The finger can act as a coupled finger before reaching the object, with all its joints rotate at the same time. Once touching the object, the finger will self-adapt to the objects as its joints can separately change their locations for the objects. The COSA finger makes use of the advantages of both the coupled one and the self-adaptive one, and solves the problem of both to some extent. Some solutions have been proposed to achieve COSA grasping mode, which will be discussed in detail in the following section. Most of the solutions have problems in some crucial aspects though achieving COSA mode, making the systems less efficient.

In order to resolve the problem of COSA fingers, a novel COSA finger with an upside-down actuator placed in proximal phalanx (called COSA-UDA finger in short) is proposed in this paper, sufficiently utilizing the place in proximal phalanx while emancipating the place in the palm.

II. COUPLED AND SELF-ADAPTIVE GRASPING

2.1 Principle of COSA Grasping

The Coupled and Self-adaptive (COSA) grasping mode is the combination of both the coupled and the self-adaptive grasping mode. The action process of the COSA finger can be
2.2 Traditional Solutions for COSA Grasping

During the first stage, or the coupled stage, the proximal joint of the finger rotates by $\theta$, while the distal joint rotates by an angle $t\theta$ as well, as the two joints are coupled together. The proportion of the rotating angle between the distal joint and the proximal joint is $t$ here, which can be set in advance to any proper certain proportion by changing the structure of the coupling mechanism. Commonly, we have

$$t = \frac{r_1}{r_2} > 1$$

Here, $r_1$ and $r_2$ respectively refer to the radius of the driving wheel and the driven wheel. Thus, the finger acts as a coupled finger in the first stage.

The coupled stage ends when the finger touches the object, and it changes into the second stage called the self-adaptive stage only on condition that the proximal phalanx touches the object earlier than the distal phalanx. Otherwise, the finger will grasp the object by pinch mode or wrap grasping mode, achieving the grasping process.

In the second self-adaptive stage, the proximal phalanx is blocked by the object, while the distal phalanx continues to move with the rotation of the distal joint once decoupling is carried out. The action process does not come to an end until the distal phalanx touches the object, marking that the finger has already hold the object by wrap grasping mode.

The COSA grasping includes pre-shaping in the first coupled stage and self-adaptation in the second stage. In this way, the COSA finger can be better prepared for grasping than the coupled finger or the self-adaptive one. However, here comes the question: how to achieve coupling at first and decoupling automatically when touching the object? That should be the solutions for COSA grasping.

3.1 Structure of COSA-UDA Finger

Unlike traditional COSA fingers, the novel COSA-UDA finger is designed in a new way. The structure of a typical COSA-UDA finger is shown in Fig 1. The COSA-UDA finger mainly consists of a base, an actuator with a reducer, a proximal phalanx, a distal phalanx, a proximal joint-shaft, a distal joint-shaft, 1st-driving-mechanism and a spring.
As shown in Fig 1, one of the most important design in COSA-UDA finger is the upside-down motor together with the reducer, fixed in the proximal phalanx. The motor is linked to the reducer which is related to the proximal joint-shaft through 2nd-driving-mechanism. Thus, the torque produced by the motor can be transmitted to the proximal joint-shaft after adjusted by the reducer. The proximal and the distal joint-shaft are parallel to each other. The proximal joint-shaft is set in the base with the proximal phalanx set on the shaft, while the distal joint-shaft is set in the proximal phalanx with the distal phalanx fixed on the shaft. The 1st-driving mechanism is composed of a driving wheel and a driven wheel, with the driving wheel fixed on the proximal joint-shaft and the driven wheel fixed on the distal joint-shaft. The wheels link to each other directly or through other transmissions, making the two wheels rotate in opposite direction. The spring connects the proximal joint-shaft to the base.

3.2 A typical COSA-UDA finger with two tender transmissions

The structure of a typical COSA-UDA finger with two tender transmissions is shown in Fig 1 above. The 1st-driving-mechanism in this typical finger consists of a driving wheel fixed on the proximal joint-shaft, a driven wheel fixed on the distal joint-shaft and two tender transmissions connecting the joint-shafts. In this typical finger, two ropes are used as transmissions. One end of the 1st-sub-transmission is fixed on the driving wheel while the other end is fixed to the driven wheel, the whole rope forming a shape of “S”. Similarly, the 2nd-sub-transmission, which is also a rope, whose ends are fixed to the driving wheel and the driven wheel separately, forms a shape of “Z” between two wheels. Thus, the two ropes forms a shape of “8”, making it possible for the driven wheel to rotate in the opposite direction comparing to the driving wheel.

In this typical finger, the 2nd-driving-mechanism, which connects the output shaft of the reducer with the proximal joint-shaft, consists of two bevel gears, which mesh with each other. The first bevel gear is fixed on the output shaft of the reducer, while the second bevel gear is fixed on the proximal joint-shaft. As a result, the 2nd-driving-mechanism is able to achieve the function that transmits the actuator’s torque to the proximal joint-shaft, which is perpendicular to the output shaft of the actuator.

The specific structure of this typical COSA-UDA finger is shown in Fig. 2. In this figure, the connecting relationship is described clearly in detail and the structure is optimized to some extent. The bevel gears, the wheels as well as the arrangement of the joint-shafts are adjusted for actual use. The base and the phalanxes are divided in detail. The dimension of some elements of the finger is revised as a result.

3.3 Grasping Principle of COSA-UDA Finger

The grasping process of COSA-UDA finger is shown in Fig 3. Take the typical finger above for example. Same as traditional COSA grasping mode, the grasping process of COSA-UDA finger can be divided into two stages, with the first stage called the coupled stage and the second stage called the self-adaptive stage. However, when we look into the mechanism that helps the COSA-UDA finger achieve COSA in a special way, this finger is distinctive during both stages.
and as the base cannot rotate, the actuator will rotate itself together with the proximal phalanx by the same angle $\alpha$. The coupling function is achieved by the 1st-driving mechanism. Once the relative position of proximal joint-shaft and the distal joint-shaft is changed, the driven wheel will rotate by the angle $\alpha$ relating to the driving wheel, for the wheels are connected by the sub-transmissions and cannot rotate separately. As a result, the distal joint-shaft together with the distal phalanx will also rotate by the angle of $\alpha$. The coupled stage ends when the finger touches the object.

The second self-adaptive stage begins only when the proximal phalanx touches the object while the distal phalanx does not. The actuator continues to run, rotating the proximal joint-shaft. Now that both the base and the proximal phalanx cannot rotate, the spring between the proximal joint-shaft and the base will deform, making it possible for the proximal joint-shaft to rotate separately against the proximal phalanx. Suppose that the proximal joint-shaft rotates by an angle $\beta$. As the coupling function of the 1st-driving mechanism demonstrated above remains to be effective, the distal joint-shaft, together with the distal phalanx, will rotate by the angle of $\beta$. The coupled stage ends when both the proximal phalanx and the proximal phalanx touch the object, with the grasping process finished.

IV. FORCE ANALYSIS OF COSA-UDA FINGER

The force analysis of the COSA-UDA finger is illustrated in Fig 4. It is supposed that the finger grasps the object after the self-adaptive stage.

![Fig. 4. Force Analysis of COSA-UDA Finger](image)

The meanings of the symbols in Fig 4 are explained below.

- $F_i$: The pushing effect that the object has on the proximal phalanx, N
- $F_d$: The pushing effect that the object has on the distal phalanx, N
- $F_r$: The equivalent resisting effect that the rope has on wheel, N
- $T_M$: The torque provided by the actuator, Nmm
- $T_S$: The resisting torque provided by the spring, Nmm
- $r_1$: The radius of the driving wheel, mm
- $r_2$: The radius of the driven wheel, mm
- $\alpha$: The rotating angle of the proximal phalanx relating to the base, °
- $\beta$: The rotating angle of the distal phalanx relating to the distal phalanx, °
- $l_0$: The distance between the proximal joint-shaft and the distal joint-shaft, mm
- $l_1$: The arm of $F_i$ relating to the proximal joint-shaft, mm
- $l_2$: The arm of $F_d$ relating to the distal joint-shaft, mm

The torque effort on the proximal joint-shaft should be balanced, thus we have,

$$T_M = T_s + F_i l_1 + F_d (l_0 + l_2 \cos \beta) \quad (1)$$

Similarly, the torque effort on the distal joint-shaft should be balanced, thus,

$$F_d l_2 = F_i r_2 \quad (2)$$

The relationship below is obvious,

$$T_M - T_s = F_i r_1 \quad (3)$$

As the spring is set between the base and the proximal joint-shaft, it deforms only when the joint-shaft rotates separately from the base, which happens during the self-adaptive stage. The deformation of the spring is determined by the rotating angle of the proximal joint-shaft as well as the distal one after the proximal phalanx is blocked by the object. The proximal phalanx has rotated by an angle $\alpha$ in advance, so we can have,

$$T_s = k \left( \frac{\beta}{t} - \alpha \right) \quad (4)$$

Here $k$ is the coefficient of the spring, whose unit should be Nmm/°. As set above, $t$ is the rate of the driving wheel’s radius over the driven wheel’s radius.

From the above equalities, we can get the solution,

$$\begin{align*}
F_i &= [T_M - k(\beta/t - \alpha)] (1 - \frac{l_0 + l_2 \cos \beta}{l_1}) \frac{1}{l_1} \\
F_d &= [T_M - k(\beta/t - \alpha)] \frac{1}{l_2}
\end{align*} \quad (5)$$

In order to grasp the object firmly, $F_i$ and $F_d$ should both be positive. According to the solution above, the following relationship should be satisfied,

$$\frac{l_0 + l_2 \cos \beta}{l_1} < 1 \quad (6)$$

$$T_M > T_s = k \left( \frac{\beta}{t} - \alpha \right) \quad (7)$$

Inequality (7) is easy to satisfied, as the torque given by the spring is usually small enough comparing with the actuator’s torque, and as the rotating angle during the self-adaptive stage is always small.

From inequality (6), we have,
\[ t > \cos \beta + \frac{l_1}{l_2} \]  

(8)

The worst situation is that the object is enormous enough, which means \( \beta \approx 0^\circ \). As discussed above, \( t \approx 0 \) is a necessary condition in this mechanism.

What is more, as the proximal phalanx becomes longer comparing to the distal phalanx, the driving wheel should become bigger comparing to the driven wheel as well. If we reasonably suppose that \( l_0 \geq 2l_2 \), together with the condition \( \beta \approx 0^\circ \), we can come to the result that,

\[ t = \frac{r_1}{r_2} > 3 \]  

(9)

In conclusion, in order to assure the object to be grasped firmly, the distal phalanx and the proximal phalanx should not be quite different in size. Moreover, the driving wheel should be bigger enough than the driven wheel.

Suppose that \( T_m = 100 \text{Nmm}, k=0.5 \text{Nmm}^2, r=4, l_0=100 \text{mm}, l_1=60 \text{mm}, l_2=50 \text{mm} \). When the range of angle \( \alpha \) and \( \beta \) is from \( 0^\circ \) to \( 90^\circ \), we can get the relationship among \( F_1, F_2, \alpha \) and \( \beta \). As shown in Fig 5, \( F_1 \) will increase as \( \alpha \) or \( \beta \) increases. Meanwhile, \( F_2 \) will increase as a result of the decrease of \( \alpha \) or the increase of \( \beta \), and the influence of \( \beta \) seems to be greater than that of \( \alpha \). However, it cannot be ignored that the value of \( F_2 \) is to some extent smaller than that of \( F_1 \), so some measures should be taken to increase the value of \( F_2 \) as well as decrease the value of \( F_1 \). Such measures include decreasing the angle \( \alpha \), adjusting the size of the proximal phalanx and the distal phalanx and so on.

V. ADVANTAGES OF COSA-UDA FINGER

The COSA-UDA finger has the following advantages.

First of all, this finger has all the advantages of traditional finger, as it makes use of upside-down actuator and only one spring to achieve COSA grasping mode. On one hand, this finger can rotate both of its joint-shafts together in an effective and anthropomorphic way. On the other hand, the finger can self-adapt to different shapes of objects.

In addition, this finger originally places the actuator into the proximal phalanx in an upside-down mode, sufficiently utilizing the place in proximal phalanx while emancipating the place in the palm or base. In contrast to traditional COSA finger, the COSA-UDA finger places the actuator in the proximal phalanx, rotating the phalanx itself when the actuator works. In this way, the structure of the finger can be much more compact than traditional COSA finger, and the place in the palm remains enough to settle down more precise instruments.

Furthermore, the deformation of the spring is little during the grasping process. The finger can be stopped at any time of the process, leading to the low amount of wasted power. Additionally, this COSA-UDA finger is cheap in manufacturing and maintaining, which is advantageous for the finger’s practical application.

However, the improvement that placing the actuator in the proximal phalanx will make the phalanx a bit heavier and bigger, which may affect the flexibility of the finger. This problem can be solved by choosing more effective motor, and can be considered as the less important one on contrast with the significant optimizing of the place in palm.

VI. CONCLUSIONS

The coupled and self-adaptive under-actuated (COSA) grasping mode is ameliorated in this paper. The COSA grasping mode includes the first coupled stage and the second self-adaptive stage. A COSA finger with upside-down actuator (COSA-UDA) is proposed. The COSA-UDA finger contains an important mechanism mainly including an upside-down actuator set in the proximal phalanx. Through force analysis, it is emphasized that the size of the phalanges should be corresponding and the driving wheel should be bigger. The pushing effect the object has on the distal phalanx is usually smaller than that on the proximal phalanx, so it is necessary to increase the force produced by the distal phalanx. The COSA-UDA finger makes full use of the place in phalanx and remains enough space for complicated instruments to be set. It is reasonable to come to the conclusion that the COSA-UDA finger is a feasible optimal design for COSA grasping mode.

REFERENCES


