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DEVELOPMENT OF MULTI-FINGERED ROBOTIC HAND WITH COUPLED AND DIRECTLY SELF-ADAPTIVE GRASP

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This paper presents a coupled and directly self-adaptive underactuated (CDSA) grasp mode, which has hybrid functions: coupled grasp and directly self-adaptive grasp. A novel multi-pulley-belt finger mechanism with springs is designed based on CDSA grasp mode. Compared with traditional coupled underactuated fingers or directly self-adaptive underactuated fingers, the grasp process of the new finger is more humanoid and its stability is better. Force analysis and size optimization rules of the finger are given. A multi-fingered robotic hand, CDSA hand, based on the CDSA finger is developed, whose control system adopts a digital signal processor (DSP) circuit module with a keyboard as its communication interface. The CDSA hand has five fingers, six DC motors, and 15 joint DOF, nine of which are CDSA joint DOF. The appearance and actions of CDSA hand imitate human hand, whose size is 1.5 times of human hand. CDSA hand weighs 1.6 kg and can grasp objects up to 0.5 kg. Simulation and experimental results show that CDSA hand is able to realize CDSA grasp mode effectively.

Keywords: Multi-fingered robotic hand; grasp mode; underactuated grasp; coupled finger; self-adaptive finger.

1. Introduction

Various kinds of robots have been widely used in the industrial processes. Service robots[1,2] are being developed for the handicapped and medical applications. To carry out a variety of service activities, a robot needs at least one hand that can grasp and manipulate various objects.[3] Humanoid robotic hands become focus of intelligent robot research for some characteristics of it, like many degrees of freedom (DOF), small volume, powerful output and complex control. For these and other reasons, the study of multi-fingered robot hands has greatly interested the research community since the early days of robotics.

Over the past three decades, research on dexterous hand has gained lot of achievements. Generally speaking, a dexterous hands has $3 \sim 5$ robot fingers with $2 \sim 4$ DOF each finger, whose joints are mostly driven by actuators actively. Examples of dexterous hands include Stanford/JPL Hand,[4] Utah/MIT Hand,[5] DLR series hands,[6,7] Robonaut Hand,[8] Shadow series hands, UB hands,[9] BH series hands by Beihang University and DLR/HIT series hands[10–12] by Harbin Institute of Technology. Dexterous hands highly depend on the sensors, algorithms and control systems. The complexity of dexterous hands makes them high cost and low reliability.

Underactuated robot hands can overcome some drawbacks of dexterous hands. In recent 10 years, they become more and more important in the field of robot hand research.

Generally speaking, an underactuated robot hand consists of a palm and several underactuated fingers. The number of actuators of an underactuated finger is less than its DOF.

On the basis of grasp mode of traditional underactuated fingers, they could be classified into two kinds: coupled underactuated fingers and directly self-adaptive underactuated fingers.

Take a two-joint coupled finger as an example to explain the action process of them. If the first joint rotates, the second joint will rotate by an angle with a fixed proportion to the rotational angle of the first joint. The rotational proportion of the first joint and the second joint is determined by the coupled mechanisms. Typical coupled hands include Southampton Hand,[13] MANUS-Hand,[14] TBM Hand[15] and SDM Hand.[16–18]

The adaptation is designed as a main function of directly self-adaptive underactuated fingers. This kind of robot fingers can self-adapt to different sizes and shapes of objects. Typical self-adaptive underactuated hands include SARAH Hand,[19] underactuated hands designed by HIT, LARM Hand,[20] underactuated hands designed by BH University,[21] TH-3R Hand[22] and GCUA Hand.[23]

Briefly, the grasp ability of directly self-adaptive underactuated hands is better than coupled underactuated hands while the grasp motion of coupled underactuated hands is more similar to human hands.

This paper studies on underactuated grasp mode under unstructured environment and low cost underactuated robotic hands.

2. Principle of CDSA Function

In this section, the traditional underactuated fingers' features will be discussed first. Then, a coupled and directly self-adaptive underactuated (CDSA) grasp mode is presented. The relationship of coupled and self-adaptive underactuated (COSA) grasp mode, CDSA grasp mode, coupled and indirectly self-adaptive underactuated (CISA) grasp mode is introduced next. Fourth, a CDSA mechanism is designed to realize the CDSA grasp mode. At the end of this section, force analysis and size optimization rules of the CDSA mechanism are given.

2.1. *The characteristics of traditional underactuated grasp modes*

During the grasp process of a coupled finger, all joints of it rotate at the same time. The grasp motion of coupled fingers is closely similar to human fingers. In addition, coupled fingers are good at grasping objects with pinch motion.

However, coupled underactuated fingers cannot self-adapt to different sizes and shapes of objects, while they cannot closely wrap objects. The upper phalanges may not touch the objects when the lower phalanges are blocked by the objects, which are shown in Fig. 1. Thus, this type of hands is not a good universal gripper.

Directly self-adaptive underactuated fingers can adjust their motion to the different sizes and shapes of objects. This kind of fingers has a good adaptability. The self-adaption is the main virtue of them. Compared with coupled underactuated fingers, the grasp ability of directly self-adaptive underactuated fingers is improved.

But directly self-adaptive underactuated fingers cannot bend the middle joints before contacting the grasped objects, which limits its appearance during grasping objects and ability to grasp small objects. The grasp process of directly self-adaptive underactuated fingers is shown in the Fig. 2.

2.2. *CDSA grasp mode*

Aiming to overcome the shortcomings and combining the merits of traditional underactuated hands, this paper presents a CDSA grasp mode.

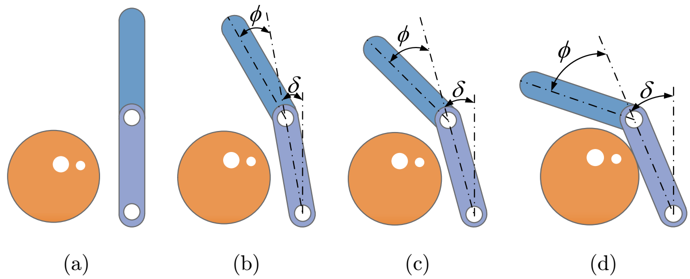


Fig. 1. Grasp process of two-joint coupled underactuated finger.

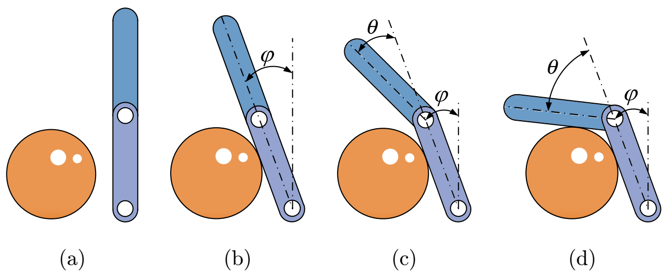


Fig. 2. Grasp process of two-joint directly self-adaptive underactuated finger.

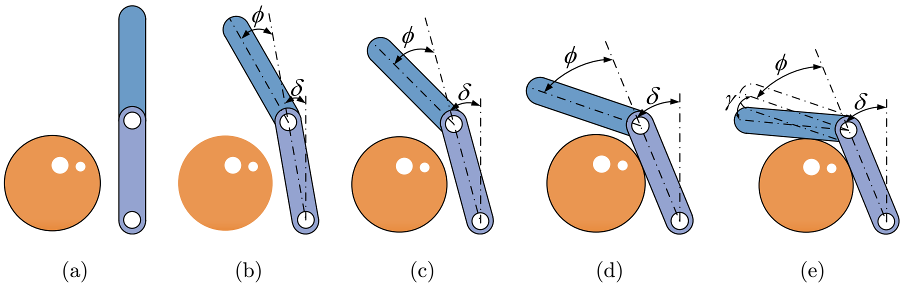


Fig. 3. Underactuated grasp process of the CDSA finger.

The CDSA grasp mode includes two stages: coupled grasp and directly self-adaptive grasp. It means that the joints of robot finger rotate at the same time when the finger approaches the objects gradually, which makes the motion of finger very human-like. After the robot finger touches objects, it can self-adapt to different objects, which improves the finger's adaptability.

Therefore, the robot fingers with CDSA grasp mode have self-adaption and coupled function. Their grasp ability and motion appearance are better than traditional underactuated fingers. CDSA robot fingers represent a new path for innovation in robotic finger design. Figure 3 is the grasp process of CDSA mode.

2.3. *The relationship of COSA, CDSA, CISA*

Aiming to overcome some drawbacks of traditional underactuated grasp mode, COSA grasp mode, CDSA grasp mode and CISA grasp mode are proposed. Figure 4 shows the relationship among them.

Based on the differences of self-adaption grasp process, the COSA grasp mode could be classified to CISA grasp mode and CDSA grasp mode. For example, a two-joint finger of CISA grasp mode has one receiver in the first phalanx. Before the receiver touches objects, finger moves with coupled grasp mode. As soon as the first phalanx is blocked by objects, receiver will drive the second phalanx rotate. It is a kind of indirect self-adaption, because there must be receivers in the CISA fingers.

Compared with CISA fingers, two-joint CDSA fingers do not need receivers in them. As soon as the first phalanx is blocked by objects, the two-joint CDSA finger can self-adapt to the shapes of objects without receivers. CDSA grasp mode has direct self-adaption.

2.4. *CDSA mechanism*

The components of the CDSA mechanism are shown in Fig. 5.

The motor is fixed in the base. The first shaft is located within the base and revolves both within the base and the lower part of the first phalanx; the second shaft is located further from the base and revolves within the upper part of the first phalanx and the second phalanx.

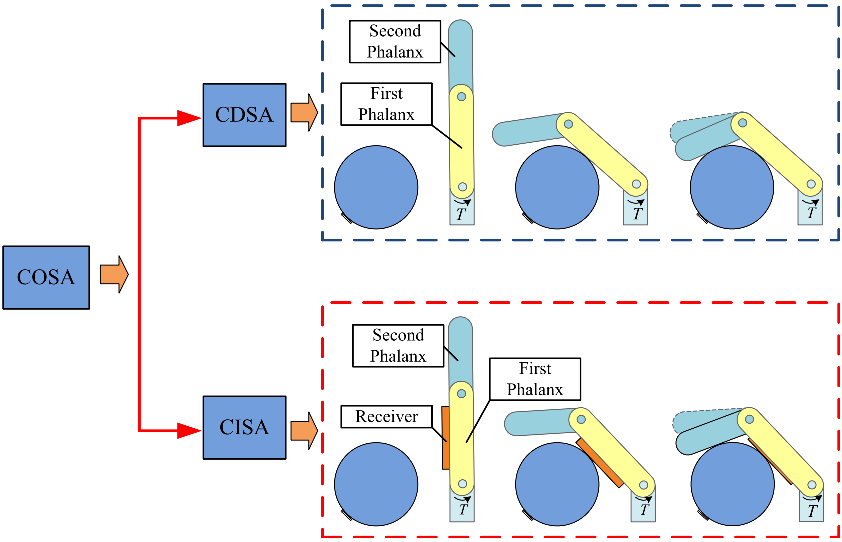


Fig. 4. The relationship of COSA, CDSA, CISA.

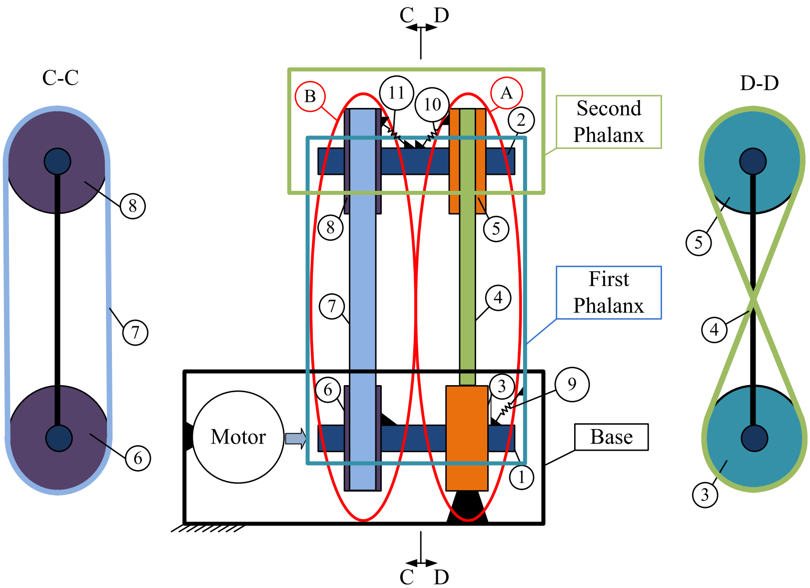


Fig. 5. CDSA mechanism. (1) the first shaft; (2) the second shaft; (3) the fixed pulley; (4) the first belt; (5) the first passive pulley; (6) the second active pulley; (7) the second belt; (8) the second passive pulley; (9) the first spring; (10) the second spring; (11) the third spring; (A) coupled mechanism; (B) directly self-adaptive mechanism.

The fixed pulley envelops the first shaft and is fixed to the base; the first passive pulley envelops the second shaft and is fixed to it; the first belt connects the fixed pulley and the first passive pulley. These are the main components of the coupled mechanism.

The second active pulley envelops the first shaft and is fixed to it; the second passive pulley envelops the second shaft and is fixed to it; the second belt connects the second active pulley and the second passive pulley. These are the main components of directly self-adaptive mechanism.

Besides pulley-belt mechanism, linkage mechanism, gear mechanism, gear-rack mechanism, sprocket-chain mechanism and tendon mechanism also can be applied to make up coupled mechanism and directly self-adaptive mechanism.

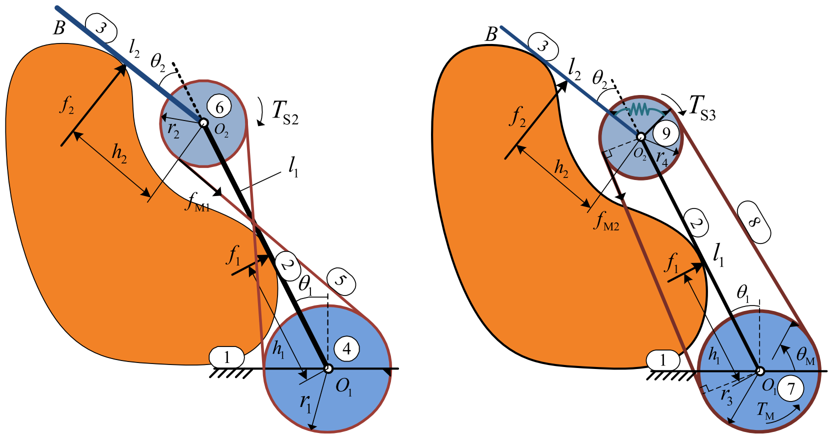
In addition, the first spring connects the first shaft and the first phalanx; the second spring connects the second shaft and the first passive pulley; the third spring connects the second shaft and the second passive pulley.

Here is the working process of CDSA mechanism. This paper supposes that the second spring and the third spring have the same elasticity in order to explain the function process of the CDSA mechanism clearly.

When the motor starts to rotate, it will drive the first shaft to rotate by an angle α. The first phalanx rotates by the same angle α. The second shaft rotates by the same angle α as a result of the coupled mechanism functioning. At the same time, the directly self-adaptive mechanism keeps the second phalanx static relative to the first phalanx. There is a conflict here. For the existence of the springs between the two mechanisms, the final effect is that the second shaft rotates by the angle of $\alpha/2$. The second and the third springs deform both. The first phalanx cannot rotate until the finger is in contact with the object. The motor continues rotating and drives the first shaft to rotate. Under the action of the first spring, the first phalanx will wrap around an object more and more tightly. The coupled mechanism cannot work any longer while the directly self-adaptive mechanism can keep on working. The second active pulley drags the second passive pulley through the second belt. The second passive pulley is connected with the second shaft by the third spring. The deformation of the third spring gradually becomes smaller and will ultimately be opposite to its original deformation. In this process, because the second spring keeps on deforming, the coupled mechanism will not block rotation of the second shaft. The second phalanx, fixed with the second shaft, rotates until it also touches the object. At this time, the CDSA finger completes the grasp task.

2.5. *Force analysis of CDSA mechanism*

The grasp process of CDSA mechanism consists of coupled grasp and directly self-adaptive grasp. The following force analyses are based on these two modes. Figure 6(a) shows the static force analysis of coupled grasp mode. Figure 6(b) shows the force analysis of directly self-adaptive grasp mode. O_1O_2 stands for the first phalanx, O_2B stands for the second phalanx. O_1 and O_2 are the centers of the first



(a) Coupled grasp process

(b) Directly self-adaptive grasp process

Fig. 6. The force analysis of CDSA mechanism. (1) base; (2) first phalanx; (3) second phalanx; (4) fixed pulley; (5) first belt; (6) first passive pulley; (7) second active pulley; (8) second belt; (9) second passive pulley.

and second shafts. $O_1O_2 = l_1$ and $O_2B = l_2$.

f_1-the force exerted on the first phalanx by the object, N;
f_2-the force exerted on the second phalanx by the object, N;
T_M-the torque of the motor exerts on the second active pulley in relation to O_1, Nmm;
T_{S2}-the torque of the second spring between the distal shaft and the first passive pulley to the distal shaft in relation to O_2, Nmm;
T_{S3}-the torque of the third spring between the distal shaft and the second passive pulley to the distal shaft in relation to O_2, Nmm;
f_{M1}-the force exerted on the first passive pulley by the first belt, N;
f_{M2}-the force exerted on the second passive pulley by the second belt, N;
r_1, r_2, r_3, r_4-the radius of the fixed pulley, the first passive pulley, the second active pulley, the second passive pulley, mm;
h_1-the arm of force of f_1 relative to O_1, mm;
h_2-the arm of force of f_2 relative to O_2, mm.

According to the principle of virtue work, the following relationship is arrived at

$$T\Omega = FV, \tag{1}$$

where T is the input torque vector by the motor and the springs, F is the grasp force vector by the two phalanxes of the finger and V is the velocity vector of the contact points.

$$T = (T_M \quad T_{S2} + T_{S3}) = (T_M \quad K_2\theta_2 + K_3\alpha), \tag{2}$$

$$F = (f_1 \quad f_2), \tag{3}$$

where K_2 and K_3 are the elasticity of the second spring and third spring, Nmm/rad; α is the rotational angle of the second phalanx after the first phalanx is blocked by objects, rad;

$$V = \begin{bmatrix} h_1 & 0 \\ l_1 \cos\theta_2 + h_2 & h_2 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{4}$$

$$\Omega = \begin{bmatrix} \dot{\theta}_M \\ \dot{\theta}_2 \end{bmatrix} \tag{5}$$

θ_M is the rotational angle of the motor, rad; θ_1 is the rotational angle of the first phalanx, rad; θ_2 is the rotational angle of the second phalanx relative to the first phalanx, rad. Let

$$A_V = \begin{bmatrix} h_1 & 0 \\ l_1 \cos\theta_2 + h_2 & h_2 \end{bmatrix} \tag{6}$$

Considering the function process of CDSA mechanism, the following relationship is arrived at:

$$\theta_M = \theta_1 + \alpha\frac{r_4}{r_3} = \left(1 - \frac{r_1 r_4}{r_2 r_3}\right)\theta_1 + \frac{r_4}{r_3}\theta_2 \tag{7}$$

Differentiating Eq. (7), the following relationship holds:

$$\dot{\theta}_M = \left(1 - \frac{r_1 r_4}{r_2 r_3}\right)\dot{\theta}_1 + \frac{r_4}{r_3}\dot{\theta}_2 \tag{8}$$

Combining Eqs. (5) and (8), the following relationship holds:

$$\Omega = A_\Omega \Theta \tag{9}$$

In Eq. (9),

$$\Theta = \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{pmatrix}, \quad A_\Omega = \begin{pmatrix} 1 - \dfrac{r_1 r_4}{r_2 r_3} & \dfrac{r_4}{r_3} \\ 0 & 1 \end{pmatrix}$$

Combining all the equations, the following relationship is arrived at:

$$TA_\Omega = FA_V \tag{10}$$

Then the following relationship is arrived at:

$$F = TA_\Omega A_V^{-1} \tag{11}$$

Let $A_C = A_\Omega A_V^{-1}$, the following relation holds:

$$F = TA_C \tag{12}$$

The following relationship is arrived at:

$$A_C = \begin{pmatrix} \frac{1}{h_1}\left(1 - \frac{r_1 r_4}{r_2 r_3}\right) - \frac{r_4}{r_3 h_1 h_2}(l_1 \cos\theta_2 + h_2) & \frac{r_4}{r_3 h_2} \\ -\frac{1}{h_1 h_2}(l_1 \cos\theta_2 + h_2) & \frac{1}{h_2} \end{pmatrix} \tag{13}$$

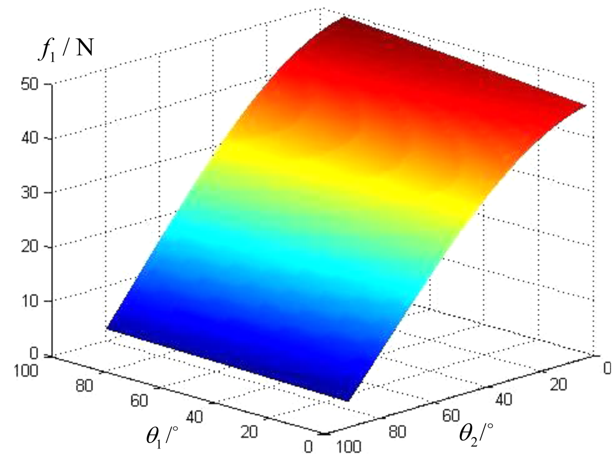
Combining all the above equations, the following relation is arrived at:

$$\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} \frac{T_M}{h_1} - (l_1 \cos\theta_2 + h_2)\frac{1}{h_1}\left[\frac{r_1}{r_2}\frac{K_3}{h_2}\theta_1 + \left(\frac{r_2}{r_1} + \frac{r_4}{r_3}\right)\frac{T_M}{h_2} - (K_2 + K_3)\frac{\theta_2}{h_2}\right] \\ \frac{r_1}{r_2}\frac{K_3}{h_2}\theta_1 + \left(\frac{r_2}{r_1} + \frac{r_4}{r_3}\right)\frac{T_M}{h_2} - (K_2 + K_3)\frac{\theta_2}{h_2} \end{bmatrix} \tag{14}$$

When $T_M = 300\,\text{Nmm}$, $r_1 = r_2 = r_3 = r_4$, the range of θ_1 and θ_2 from $0 \sim 90^\circ$, $h_1 = 50\,\text{mm}$, $l_1 = 100\,\text{mm}$, $h_2 = 30\,\text{mm}$, $l_2 = 60\,\text{mm}$, $K_2 = K_3 = 0.5\,\text{Nmm/rad}$, then the relationships of f_1, f_2, θ_1 and θ_2 are shown in Fig. 7. The conclusions from these figures are listed below.

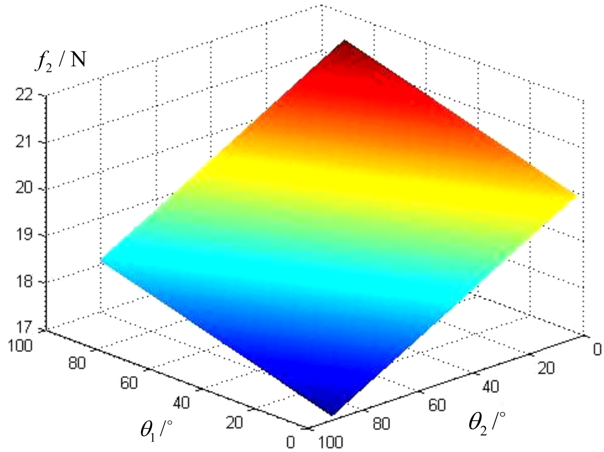
(i) When θ_1 and θ_2 increase, f_1 and f_2 will change slightly and continuously.
(ii) For θ_1 and θ_2 of any value, f_1 and f_2 will always remain positive and the values of them will be sufficiently large for the fingers to effectively grasp objects stably.

These simulation results show that the CDSA finger is effective: it can grasp objects stably.



(a) f_1 as a function of θ_1 and θ_2

Fig. 7. The relationship of values.



(b) f_2 as a function of θ_1 and θ_2

Fig. 7. (*Continued*)

2.6. *Elasticity of springs*

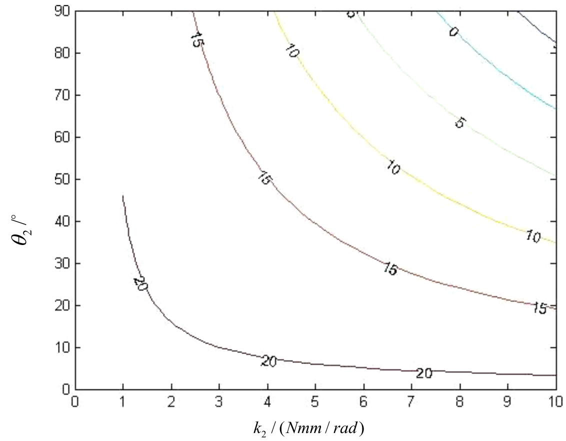
The second spring and the third spring coordinate the movements of coupled mechanism and directly self-adaptive mechanism when the CDSA mechanism works. Springs are key components of CDSA mechanism. The elasticity of springs applied in fingers will affect the stability of CDSA mechanism and even the grasp ability of CDSA fingers. The selecting of springs is an important step during design of fingers.

Depending on the above analysis, the relationship is arrived at:

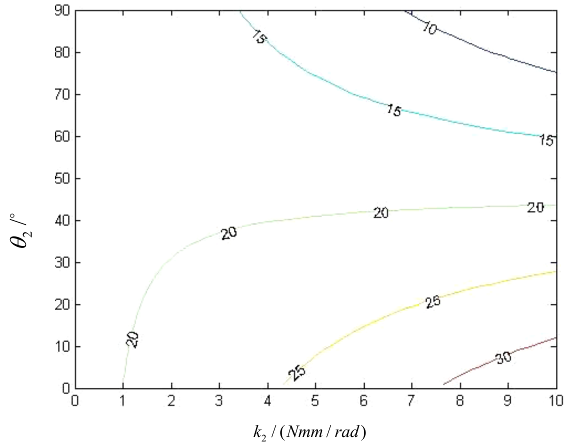
$$f_2 = \frac{r_1}{r_2}\frac{K_3}{h_2}\theta_1 + \left(\frac{r_2}{r_1} + \frac{r_4}{r_3}\right)\frac{T_M}{h_2} - (K_2 + K_3)\frac{\theta_2}{h_2} \tag{15}$$

When $T_M = 300\,\mathrm{Nmm}$, $r_1 = r_2 = r_3 = r_4$, θ_1 is $45°$, the range of θ_2 is $0 \sim 90°$, the range of K_2 and K_3 are $0 \sim 10\,\mathrm{Nmm/rad}$, $h_2 = 30\,\mathrm{mm}$, $l_2 = 60\,\mathrm{mm}$, then the relationships of K_2, θ_2 and f_2 are shown in Fig. 8(a) and the relationships of K_3, θ_2 and f_2 in Fig. 8(b).

In Fig. 7(a), when value of θ_2 has been identified, softer the second spring gets more powerful f_2. Compared with values of f_2, when value of θ_2 has been identified, tougher the third spring gets the more powerful f_2, which is shown in Fig. 7(b). It means the third spring should be tougher than the second spring. Considering the working process of a two-joint CDSA finger to understand these analysis results, the second spring makes the coupled mechanism work and the third spring makes the directly self-adaptive mechanism work. After the first phalanx touches objects while the second phalanx does not touch objects, the second spring makes the second phalanx rotate forward but the third spring makes the second phalanx rotate backward. At the end of the two-joint CDSA finger's grasp process, the deformations of second spring and third spring are opposite with each other. So the third spring should be tougher than the second spring for better grasp stability.



(a) f_2 as a function of k_2 and θ_2



(b) f_2 as a function of k_3 and θ_2

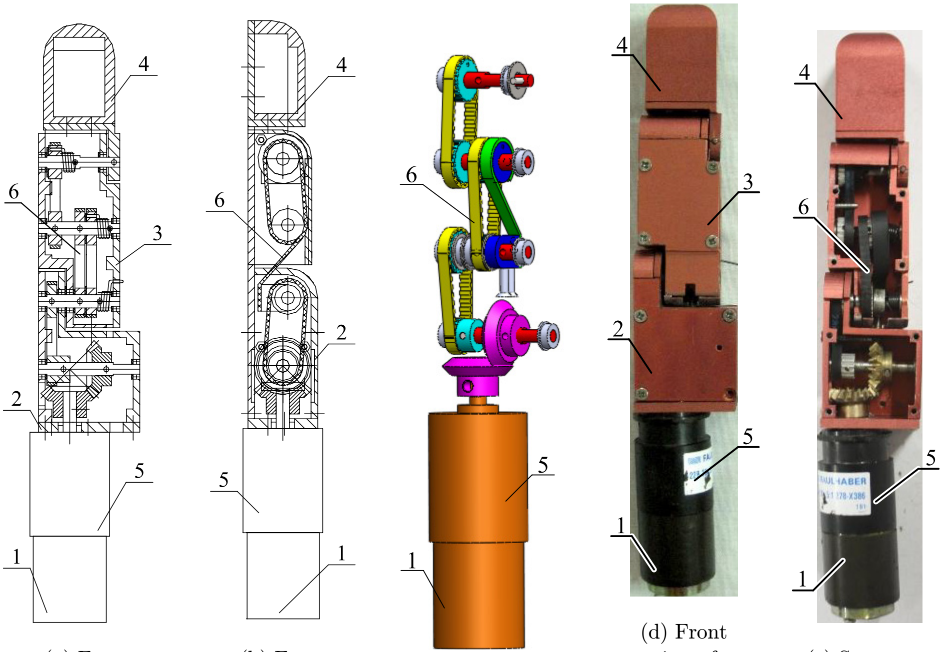
Fig. 8. The selecting of springs.

3. Design of CDSA Hand

This section will describe the design of CDSA hand which is based on the CDSA grasp mode and multi-pulley-belt mechanism.

3.1. *Structural design of the two-joint finger*

The components of the two-joint CDSA finger are shown in Fig. 9. This finger has one embedded motor to drive two joints of it. There is only one CDSA mechanism in it. In addition, the output shaft of motor is fixed with the first bevel gear, which is meshing with the second bevel gear. The second bevel gear is fixed with the first



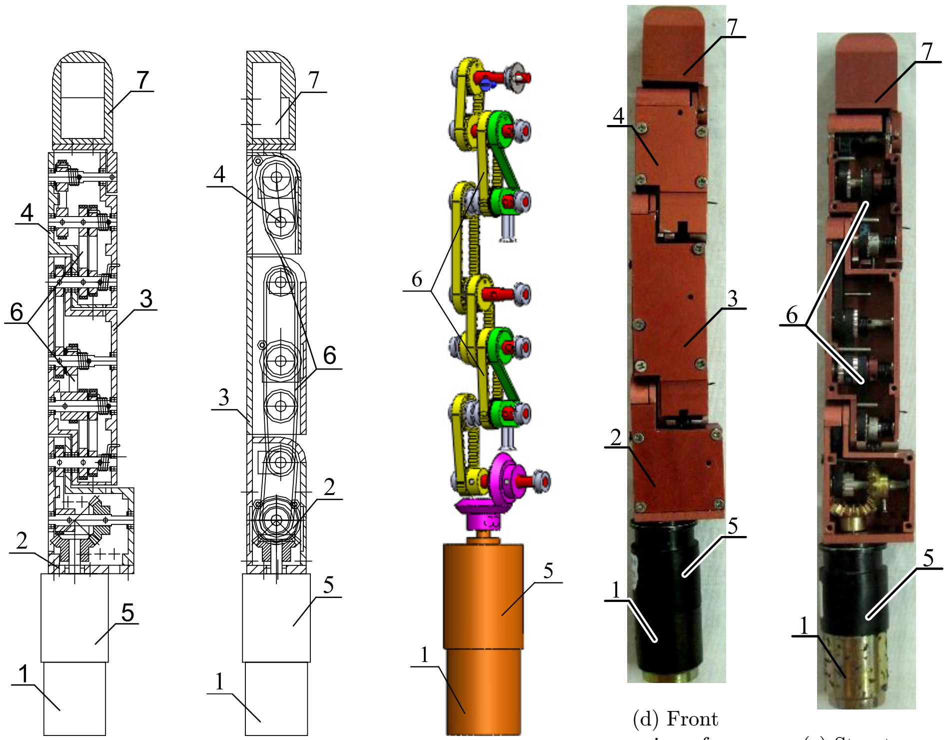
(a) Front cutaway view (b) Front cutaway view (c) 3D transmission mechanism (d) Front view of two-joint CDSA finger (e) Structure of 2-joint CDSA finger

Fig. 9. The CDSA finger with two joints. (1) motor; (2) base; (3) the first phalanx; (4) the second phalanx; (5) reducer; (6) the CDSA mechanism.

shaft. Modules of first bevel gear and second bevel gear are 1while number of teeth of them is 16. The two-joint CDSA finger has two DOF, one of which is CDSA joint DOF. It is 1.5 times the size of human hand's thumb, with finger length of 89 mm, finger width of 22 mm, finger thickness of 20 mm and rotation angle range of $0^\circ \sim 90^\circ$ for all joints.

3.2. *Structural design of the three-joint finger*

Design of the three-joint CDSA finger is shown in Fig. 10. The three-joint CDSA finger has the same design principle like two-joint CDSA finger. This finger has one embedded motor to drive three joints of it. There are two CDSA mechanisms in it. The four three-joint fingers of CDSA hand have the same structure at different sizes. The three-joint CDSA finger has three DOF, two of which are CDSA joint DOF. The middle finger is 1.5 times the size of human hand's middle finger, with finger length of 132 mm, finger width of 22 mm, finger thickness of 20 mm and rotation angle range of $0^\circ \sim 90^\circ$ for all joints. Every finger of CDSA hand can grasp objects independently with CDSA grasp mode.



(a) Front cutaway view

(b) Front cutaway view

(c) 3D transmission mechanism

(d) Front view of three-joint CDSA finger

(e) Structure of three-joint CDSA finger

Fig. 10. Three-joint CDSA finger. (1) motor; (2) base; (3) the first phalanx; (4) the second phalanx; (5) reducer; (6) the CDSA mechanism; (7) the third phalanx.

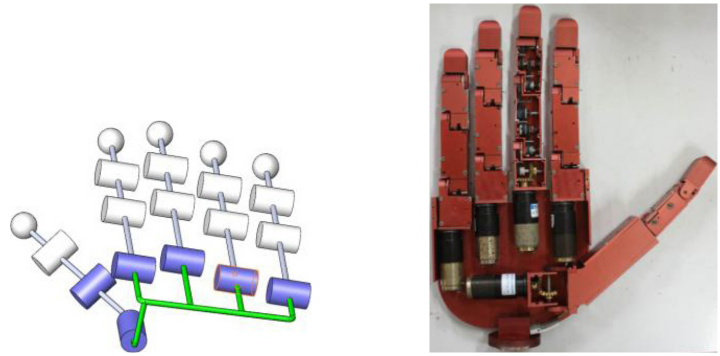
3.3. *Freedom planning and modular design of CDSA hand*

The CDSA hand has five fingers and 15 joint DOF (six active joint DOF, nine CDSA joint DOF), which is shown in Fig. 11. In Fig. 11(a), dark cylinders stand for active joint DOF and light-colored cylinders stand for CDSA joint DOF. Figure 11(b) is the motor distribution inside the CDSA hand.

In Fig. 12(a), module A is the CDSA module. Module B is the active foot joint of five fingers with one embedded actuator, reducer and gear transmission. Module C is the swing joint of the thumb in which there is one embedded actuator. Figure 12(b) is the outward appearance of CDSA hand.

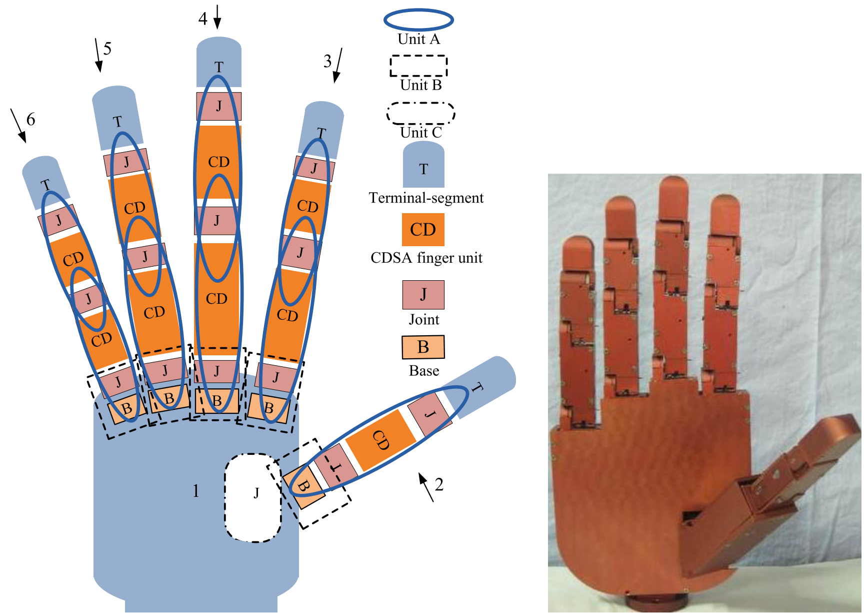
The four three-joint fingers have the same structure at different sizes, with one motor driving three joints. The palm has one motor driving the lateral swing of the base of the thumb, while the thumb has one motor driving two joints.

CDSA hand is 1.5 times the size of an adult's hand, with length of 250 mm, palm length of 144 mm, palm width of 106 mm, palm thickness of 45 mm with rotation angle range of $0^\circ \sim 90^\circ$ for all joints.



(a) Freedom planning of CDSA hand (b) Motor distribution inside the CDSA hand

Fig. 11. CDSA hand's schematic diagram and motor distribution.



(a) (b)

Fig. 12. Module division of CDSA hand.

4. Operating and Grasp Experiments of CDSA Hand

Figures 13(a)–13(c) show some pictures of the CDSA hand's fisting process. Figure 13(d)–13(f) show some pictures of the CDSA hand's pinching process. During the CDSA's action process of fisting and pinching, the robot hand can move like a

(a) (b) (c)

(d) (e) (f)

Fig. 13. CDSA hand's fisting process and pinching process.

(a) (b) (c) (d)

Fig. 14. CDSA hand's grasp process.

(e) (f) (g) (h)

Fig. 14. (*Continued*)

human hand. Before fingers are blocked by objects, all the shafts rotate simultaneously. The CDSA hand can self-adapt to different objects.

Figure 14 shows some pictures of the CDSA hand's grasp process. CDSA hand can self-adapt to objects of different sizes and shapes and can grasp the objects stably.

The experiments prove that the new CDSA grasp mode is effective and the CDSA hand can stably grasp different objects with the CDSA mode. The motion appearance of CDSA hand is highly anthropopathic and the hand can self-adaptively grasp objects stably.

5. Conclusion

This paper presents a CDSA grasp mode, which can achieve coupled grasp and directly self-adaptive grasp at the same time.

Based on the CDSA grasp mode, this paper designs a CDSA finger with multi-pulley-belt mechanism and gives the optimization rules and force analysis of CDSA finger.

A multi-fingered robotic hand, CDSA hand, based on the CDSA finger is developed, whose control system adopts a digital signal processor (DSP) circuit module with a keyboard as its communication interface. CDSA hand has five fingers, 15 joint DOF (nine of them are CDSA joint DOF). Grasp experimental results show CDSA hand is able to realize CDSA grasp mode effectively and grasps objects stably.

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