COSA-FBA Hand: An Underactuated Hand with Five-gear Mechanisms and Built-in Actuators

Siqiao Ruan, Wenzeng Zhang, Tianyi Zhang and Shuang Song

Abstract This paper proposes a novel underactuated hand, COSA-FBA hand, which performs coupled and self-adaptive grasping. The COSA-FBA hand consists of 5 fingers and 14 degrees of freedom. The COSA-FBA finger consists of an actuator embedded into its proximal phalange, a five-gear mechanism and a spring, which allows it to finish multiple grasping postures such as enveloping and pinching, depending on the shape, size, and dimension of the object. The COSA-FBA hand has advantages of concise structure, low cost, high efficiency and space-saving of the palm. The coupled and self-adaptive hand has a wide arrange of applications.

Keywords Robot hand · Underactuated finger · Coupled and self-adaptive grasp

1 Introduction

Robot hands have already played a critical role in industrial production and high-risk operation. However, there are still many human workers and operators working on the assembly line who are exposed to some life-threatening situations. In order to completely revolutionize and automate these industries, a versatile grasping tools becomes necessary. For the purpose of inventing a robot hand that is agile, easy to control, and capable of multi-tasking, humanoid hands become a direction that researchers try to approach, since human hands is capable of finishing many grasping mode and posture which can grasp the object effectively.

To imitate human hand, dexterous hands were designed and developed. Dexterous hand is the robot hand that every joint requires a motor to actuate.

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The Utah/MIT Dexterous Hand [1], Stanford/JPL Hand [2], BH Hand, DLR/HIT Hand and Robonaut hand [1] are good examples of dexterous hand.

Dexterous hand is capable of achieving multiple grasping modes like pinching, gripping, and catching. Also, through controlling each joint, the hand can adapt to the shape and size of different objects. However, the dexterous hand has many serious flaws. On one hand, the great number of DOA makes the whole hand cumbersome and expensive in cost. On the other hand, it is hard to control so many actuators spontaneously.

Due to the flaw of dexterous hands, underactuated robot hand has become a new concentration of many researchers [3]. An underactuated robot hand is defined as the robot hand that possesses less DOA (Degrees of Actuation) than DOF (Degrees of Freedom) [4]. The underactuated robot hand solves some flaws of Dexterous hand. It is cheaper, simpler in structure, and easier to control due to the fact that it has less actuators [5].

However, the traditional underactuated hands [6] usually have simplex grasping modes such as coupled, self-adaptive and parallel grasping modes. In order to diversify the grasping mode. Hybrid grasping mode underactuated hand is being proposed [7, 8]. Hybrid grasping mode combines the flexibility of dexterous hands and the stability and simplicity of traditional underactuated hands, which brings underactuated hand to a higher level.

This paper introduces a coupled and self-adaptive underactuated finger with a novel built-in actuator five-gear mechanism. Different from the existing hybrid underactuated hand, COSA-FBA hand uses two gears that sleeved on the transitional axis and connected to each other with a spring to accomplish the function of decoupling which effectively switch the grasping mode from coupling to self-adaptive, making the whole structure more compact.

The second part of this paper introduces the concept of the coupled and self-adaptive (COSA) underactuated hand, the third part analyzes the structure of the COSA-FBA finger, the fourth part analyzes the grasping-force distribution of the COSA-FBA hand, the fifth part presents the grasping experiment of the COSA-FBA finger, and the sixth part demonstrates the design of the humanoid COSA-FBA hand.

2 Concept of the Coupled and Self-adaptive (COSA) Grasp

Coupled grasping mode is the grasping mode that every joint rotates with a fixed rotating ratio. This grasping mode is similar to human grasping, and the whole grasping process is relatively stable. Nonetheless, its defect is that its grasping mode is fixed, that it cannot adapt to the shape of the object. Therefore, it has a poor performance of grasping different kinds of objects.

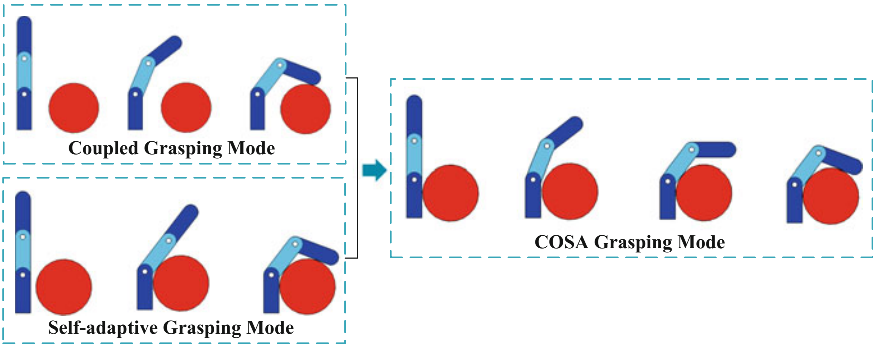

Fig. 1 Concept of coupled and self-adaptive (COSA) grasping mode

Self-adaptive grasping mode is the grasping mode that when it grasps an object, through one actuator, the first joint rotates, and the middle-phalange moves towards the object while the other joint keep static. When the middle-phalange contacts with the object, the second joint starts to rotate, and the terminal-phalange starts moving until it envelopes the object. Self-adaptive grasping mode is capable of adapt to different shapes of object. Its flaw is that its grasping posture is rigid and not personified, because when the finger does not contact with the object, the whole finger straightens. Also, when the middle-phalange squeezes the object, some objects with smooth surfaces may be pushed away, which may cause instability in the grasping process.

The COSA grasping mode combines the advantages of these two traditional grasping mode and neutralizes their disadvantages. As Fig. 1 shows, when coupled self-adaptive grasping mode is performed, the finger would first approach the object with coupled grasping mode. If the terminal-phalange makes contact with the object, the grasping process is done. If the middle-phalange contacts with the object, the next phalange would turn into self-adaptive mode and envelope the object. Coupled self-adaptive grasping mode is not only more similar to human grasping mode but also possesses the ability to adapt to the shape of object.

3 Design of the COSA-FBA Finger

3.1 Structure of the COSA-FBA Finger

As Fig. 2 shows, the structure of COSA-FBA finger is mainly composed of the base, the middle-phalange, the terminal-phalange, the actuator, the first joint-shaft, and the second joint-shaft. The first joint-shaft is fixed in the base. The second joint-shaft is sleeved on the middle-phalange. The terminal-phalange is fixed on the second axis.

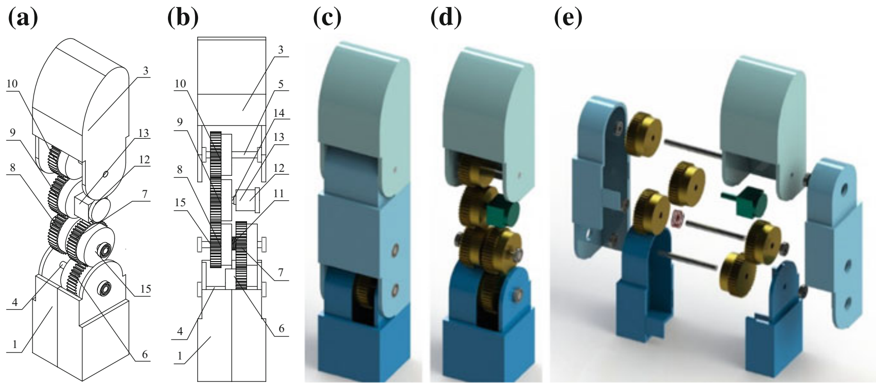

Fig. 2 The structure of COSA-FBA finger. *1* base; *2* middle-phalange; *3* terminal-phalange; *4* first axis; *5* second axis; *6* first gear; *7* second gear; *8* third gear; *9* active gear; *10* fourth gear; *11* spring; *12* motor; *13* reducer; *14* driving mechanism; *15* transitional axis

The first joint-shaft is parallel with the second joint-shaft. Furthermore, this device also contains a transitional axis, an active gear, a first gear, a second gear, a third gear, a fourth gear and a spring. The actuator is fixed on the middle-phalange. The active gear is fixed on the output axis of the actuator. The transitional axis is set in the middle-phalange. The middle-phalange is sleeved with the first joint-shaft. The first joint-shaft is parallel with the transitional axis. The active gear is meshed with the third gear. The third and the second gear are sleeved on the transitional axis. The spring is connected to the second gear and the third gear. The second gear is meshed with the first gear. The first gear is fixed on the first axis. The fourth gear is meshed with the active gear and fixed on the second axis. In this structure, a torsional spring is used as the spring. The gear ratio of the first gear and the second gear is 1. The gear ratio of the active gear and the third gear is “a”. The gear ratio of the active gear and the fourth gear is a. “a” is a positive rational number. An example of its specific structure and mechanism is shown in Fig. 2. In this example, “a” equals 1.

3.2 *Grasping Process of COSA-FBA Finger*

The grasping process is presented as Fig. 3 shows, the initial state of the finger is perpendicular with the palm, and both the first and the terminal-phalange straighten up as Fig. 3a has shown. When the grasping motion starts, the output axis of the actuator starts rotating. Through the reducer, the power is transmitted to the active gear, making it start to rotate. The active gear transmits the power to the third gear which sleeved on the transitional axis and the fourth gear which fixed on the second axis, making them start to rotate. The third gear pulls the second gear through the

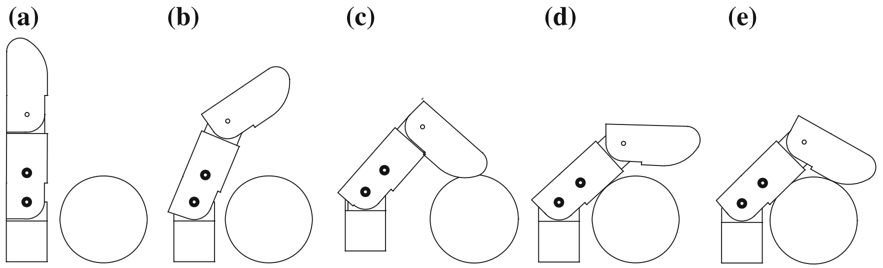

Fig. 3 The grasping process of COSA-FBA finger

twisting force of the spring. In the meantime, the second gear meshes with the first gear.

When the finger does not contact with the object as Fig. 3b has shown, the active gear drags the fourth gear which fixes on the second joint-shaft. Since the second joint-shaft is fixed on the terminal-phalange, the terminal-phalange starts rotating. Through transmission in the second and the third gear, the middle-phalange rotates around the first gear which fixes on the base. The angle that the middle-phalange rotates from its initial state and the angle between the terminal-phalange and the middle-phalange is the same. The coupling grasping process is performed.

If the terminal-phalange first makes contact with the object as Fig. 3c has shown, the fourth gear is unable to continue rotating which makes the motor stop moving. Therefore, the whole grasping process is ended. A coupling anthropopathic pinching posture is performed.

If the middle-phalange first makes contact with the object as Fig. 3d has shown, the second gear is no longer able to rotate around the first gear. However, the third gear is able to keep rotating, and the spring starts to deform. The fourth gear is still able to rotate, making the terminal-phalange keep rotating until it contacts with the object. When the terminal-phalange contacts with the object, the motor stops moving. Therefore the whole grasping process is ended as Fig. 3e has shown. A self-adaptive grasping process is performed.

4 Grasping Force Distribution Analysis of COSA-FBA Finger

This part focus on the grasping force distribution of COSA-FBA finger. For the reason of simplification, the gravity force of the finger and objects and the friction between phalanges are neglected, and the contact forces are applied on points (Fig. 4).

When the finger fully envelopes an object, the grasping force and the total arm of the force is in an equilibrium state. Based on this characteristic, several moment equations can be reached as follows (η is the percentage of transmission loss).

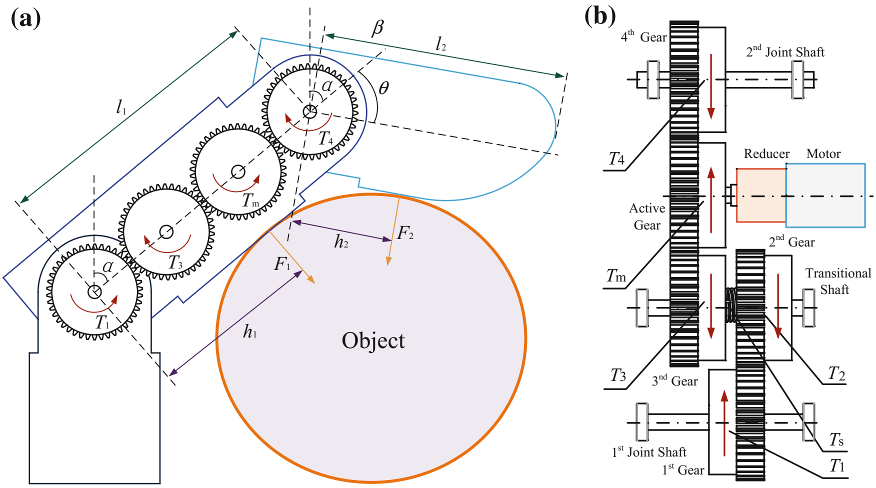

Fig. 4 Grasping-forces distribution analysis of the COSA-FBA finger. F_1, F_2—The grasping force to the object by middle-phalange and terminal-phalange, l_1, l_2—The length of middle-phalange and terminal-phalange, h_1, h_2—The arm of force F_1 and F_2, α—The rotational angle of middle-phalange, θ—The rotational angle of terminal-phalange in self-adaptive process, β—The rotational angle of terminal-phalange, T_1—Torque of the first gear, T_2—Torque of the second gear, T_3—Torque of the third gear, T_4—Torque of the fourth gear, T_m—Torque of the motor to the active gear, T_s—Torque of the spring

First, relative to the first axis, the torque relationship can be drawn as follow:

$$T_4 = F_1 h_1 + F_2 (h_2 + l_1 \cos\alpha). \tag{1}$$

Second, according to the output axis of the motor, the torque relationship can be reached as follows:

$$\eta T_m = T_4 + T_3. \tag{2}$$

Third, relative to the transitional axis, the torque relationship can be drawn as follows:

$$T_2 = T_3, \eta T_m = T_4 + T_2. \tag{3}$$

At last, according to the first axis, the torque relationship can be reached as follows:

$$T_1 = \eta T_2, T_2 = T_1/\eta. \tag{4}$$

$$\eta T_m = T_4 + T_1/\eta. \tag{5}$$

Plug Eq. (1) into Eq. (5), the torque relationship can be drawn as follows:

$$\eta T_m = F_2 h_2 + [F_1 h_1 + F_2(h_2 + l_1 \cos\alpha)]/\eta. \tag{6}$$

For the spring, according to Hooke law, the following equation can be get:

$$T_s = k\theta. \tag{7}$$

Because of $\eta T_s = T_4$, one can get:

$$\eta k\theta = T_4 = F_1 h_1 + F_2(h_2 + l_1 \cos\alpha). \tag{8}$$

Plug Eq. (8) into Eq. (6), the equation of F_2 can be drawn as follows:

$$F_2 = (\eta T_m - k\theta)/h_2. \tag{9}$$

Plug Eq. (9) into Eq. (6), the equation of F_1 can be reached as follows:

$$F_1 = [k\theta(\eta + 1) - \eta T_m]/h - [l_1 \cos\alpha(\eta T_m - k\theta)]/h_1 h_2. \tag{10}$$

Using Eq. (9) and Eq. (10), the relationship between grasping force, rotational angle, and the arm of the force are analyzed and studied.

According to Fig. 5a, the grasping force of the first phalange reaches maximum when the arm of the force is minimized and θ reaches maximum (90°). The grasping force of the second phalange reaches maximum when the arm of the force is minimized and θ reaches minimized (0°). This is because the spring would consume a large amount of the torque of the motor, so the grasping force in the coupling process is bigger than the grasping force in the self-adaptive process.

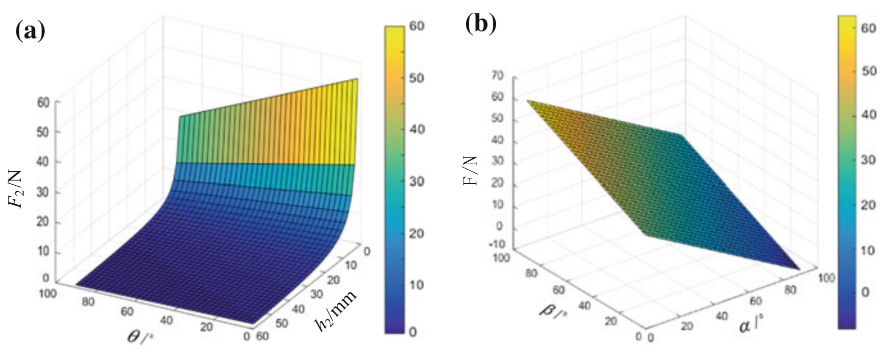

Fig. 5 Contact-force distribution by h_1, h_2, and θ, where **a** $T_m = 60$ N mm, $l_1 = 60$ mm, $k = 50$ N mm, $\alpha = 30°$, $\eta = 95\%$, $h_2 = 30$ mm **b** $T_m = 60$ N mm, $l_1 = 60$ mm, $k = 5$ N mm, $\eta = 95\%$, $h_1 = 30$ mm, $h_2 = 30$ mm

According to Fig. 5b, when the rotational angle of the first phalange increases, the grasping force of the first phalange decreases. When the rotational angle of the second phalange increases, the grasping force of the first phalange increases, while the grasping force of the second phalange decreases. This is because the two transmission routes have distributed the torque of the motor. Overall, the COSA-FBA robot finger is capable of grasping object effectively and stably.

5 Grasping Experiment of COSA-FBA Finger

To evaluate the performances of the COSA-FBA finger, several grasping experiment is conducted. Depending on the size, dimension and shape of the object, the COSA-FBA finger can perform enveloping and pinching posture when it grasps the object as Fig. 6 has shown. When the object is located on the upper side of the finger, the COSA-FBA finger would perform coupled grasping mode and pinch the object. When the object is located on the lower side of the finger, the COSA-FBA finger would perform COSA grasping mode and envelop the object. It has been proved that the COSA-FBA finger is capable of grasping object effectively and stably.

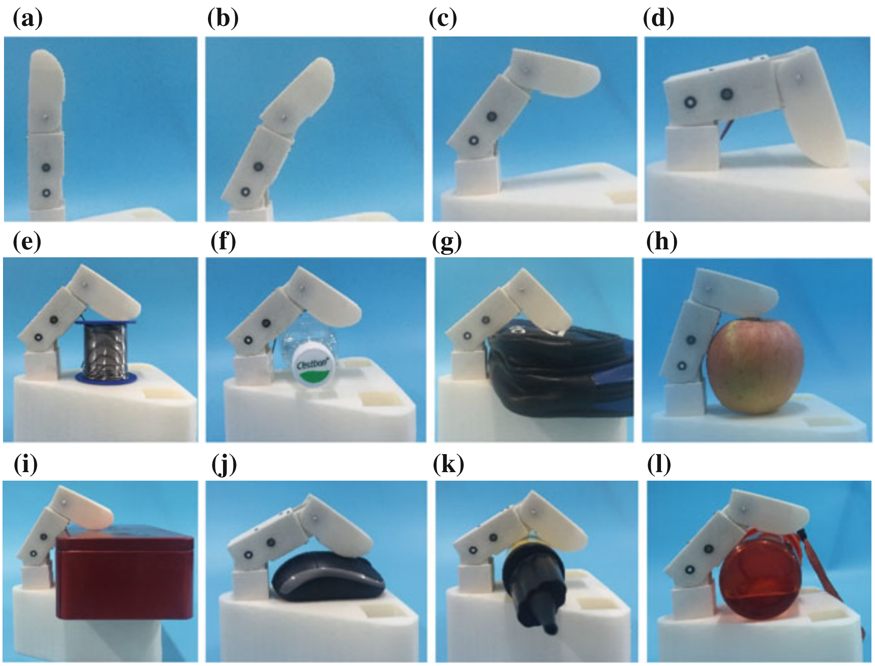

Fig. 6 Grasping experiments of COSA-FBA finger

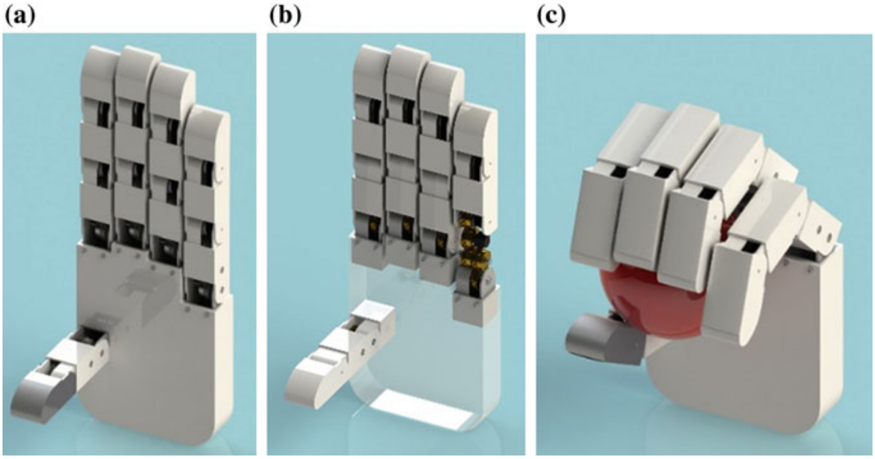

Fig. 7 COSA-FBA Humanoid Hand

6 Design of COSA-FBA Humanoid Hand

A humanoid robot hand is designed adopting the finger mechanism already described. The appearance of this humanoid hand is shown in Fig. 7. This robot hand consists of five COSA-FBA robot fingers. Each finger consists of three joints and three phalanges, except for the thumb which possess two joints and two phalanges. The second phalange can repeat the mechanism above or other coupling structure. This example uses an 8-shape pulley-belt mechanism to accomplish coupling.

7 Conclusions

This paper proposes a novel underactuated finger, COSA-FBA finger. The COSA-FBA finger has a built-in actuator, five-gear mechanism, which allow it to finish coupled and self-adaptive grasping. Its features of easy-control, anthropopathic, adaptive, and low-cost allow it to be widely used.

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