PASA-SEBA Hand: An Underactuated Hand with Seven-gear Empty-trip Mechanisms and Built-in Actuators

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***Abstract*—This paper introduces a novel underactuated hand with seven-gear empty-trip mechanisms and built-in actuators, PASA-SEBA hand. PASA-SEBA finger is able to perform parallel and self-adaptive grasping, allowing it to grip or envelop object more personified. The PASA-SEBA hand consists of 3 fingers and 6 degrees of freedom. Each PASA-SEBA finger consists of an actuator embedded into its middle phalange, a seven-gear empty-trip mechanism, and two spring. These mechanism realize a hybrid grasping mode and multiple grasping postures as well as adapting the shape, size, and dimension of the object. Geometric and force analysis have presented the force distribution and grasping process of the PASA-SEBA Hand, which indicates that the PASA-SEBA hand is reliable, adaptive, and efficient. PASA-SEBA hand is suitable for a wide arrange of applications.**

I. Introduction

At the age of robot revolution, a versatile end effector has become more necessary and demanding. Until now, human hand has been the most effective gripper. It has a large amount of DOF(Degree of Freedom), it is able to perform many postures and grasping mode, and it is capable of finishing many tasks.

Basically, the current existing humanoid multi-fingered hand can be divided into two categories: dexterous hand and underactuated hand. In order to imitate human hand, dexterous hand were designed and developed. Dexterous hand is the robot hand that every joint and every DOF driven by an actuator. The Utah/MIT Dexterous Hand[1], DLR/HIT Hand[2], Robonaut hand, and Gifu hand[4] are some intriguing example in the early research of robot hand. However, the dexterous hand has many flaws in real life applications. It is limit in dimension, cost, mechanical structure, and weight, since many motors and control system has to be implanted in the hand. Also, large grasping force and multiple grasping mode is needed.

To amend with these demands and difficulties, underactuated hands were researched and developed. An underactuated robot hand is defined as the robot hand that possesses less DOA (Degrees of Actuation) than DOF (Degrees of Freedom). 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.

Nevertheless, the traditional underactuated hands usually have simplex grasping modes such as coupled, self-adaptive and parallel, while the grasping mode of the underactuated hand is still very limited. In order to diversify the grasping mode, hybrid grasping mode underactuated hand has been proposed. 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 paralleled and self-adaptive underactuated finger with a novel built-in actuator seven-gear mechanism. Different from the existing hybrid underactuated hand, PASA-SEBA hand uses a pair of belt pulley to perform parallel grasping posture and two gears that sleeved on the transitional axis and connected by a spring with an empty-trip mechanism to accomplish the function of decoupling which effectively switch the grasping mode from parallel to self-adaptive, making the whole structure more compact.

The second part of this paper introduces the concept of the parallel and self-adaptive (PASA) underactuated hand, the third part proposes the structure of the PASA-SEBA finger, the fourth part analyzes the grasping-force distribution of the PASA-SEBA hand, the fifth part demonstrates the design of the humanoid PASA-SEBA hand, and the sixth part shows the experiment of PASA-SEBA hand.

II. Concept of the Parallel and Self-adaptive (PASA) Grasp

Parallel grasping mode is the grasping mode that the terminal phalange would always be parallel to the first phalange, while the first joint rotate towards the object and the second joint rotate in a way to preserve the parallel posture. This grasping mode is capable of enveloping and pinching the object, and the whole grasping process is relatively stable. It is especially effective in grasping thin object. However, the shape and dimension of the object it needs to be hold is relatively limited.

Different from coupled and parallel grasping, self-adaptive grasping mode is more flexible. In the process of self-adaptive motion, the first joint will start to rotate until the middle-phalange make contact to the object, while the terminal-phalange has no motion and keep straightened. When the middle-phalange pressure the object, the terminal-phalange starts to move towards the object until it fully envelops it.

*This Research supported by National Natural Science Foundation of China (No. 51575302).

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Self-adaptive mode is able to adapt the shape and dimension of the object, allowing it to have more real life usage, but it is relatively not anthropopathic. Most importantly, it is not suitable to grab object with a smooth surface, since the middle-phalange may press it away.

PASA grasping mode is the grasping mode that can accommodate the shape and position of the object with parallel grasping mode and self-adaptive grasping mode. As Fig. 1 has shown, the PASA grasping mode will first perform parallel grasping. If the terminal-phalange make contact with the object first, the whole grasping process is over, and the object is successfully pinched. If the middle-phalange first make contact with the object, the terminal phalange will turn into self-adaptive grasping mode. It will rotate towards the object until it fully envelop the object. PASA grasping mode add up the strength of parallel grasping and self-adaptive grasping. It is more practical and efficient.

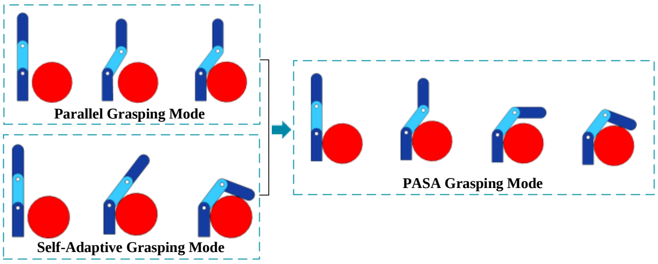

Fig. 1. Concept of parallel and self-adaptive (PASA) grasping mode

III. Design of the PASA-SEBA Hand

A. *Structure of the PASA-SEBA finger*

As Fig.2 shows, the structure of PASA-SEBA finger is mainly composed of the base, motor, reducer, the middle-phalange, the terminal phalange, the first joint-shaft, the second joint-shaft, and transitional axis. The first joint-shaft is fixed in the base and set on the middle phalange. The terminal-phalange is fixed on the second joint-shaft, and the second joint-shaft is parallel with the first joint-shaft. The output axis of the actuator is fixed on the input axis of the reducer.

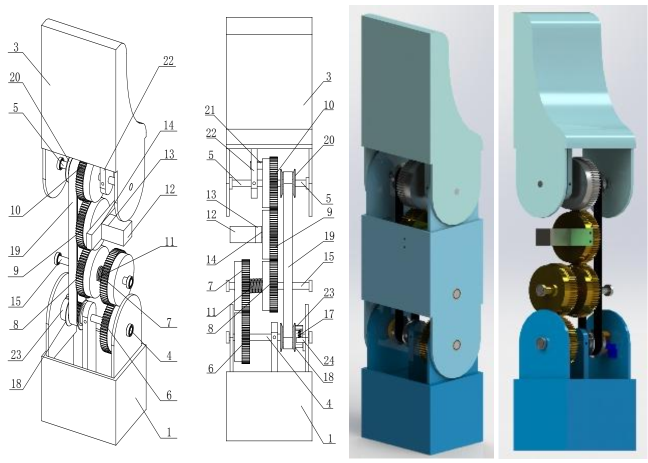

Fig. 2. The Structure of PASA-SEBA finger
1-base; 2-middle-phalange; 3-terminal-phalange; 4-first joint-shaft; 5-second joint-shaft; 6-first gear; 7-second gear; 8-third gear; 9-active gear; 10-fourth gear; 11-first spring; 12-motor; 13-reducer; 14-driving mechanism; 15-transitional axis; 16-object; 17-second spring; 18-first belt wheel; 19-trasmission module; 20-second belt wheel; 21-active block; 22-passive block; 23-limiting wheel; 24-limiting block

Furthermore, this device also contains transitional axis, an active gear, a first gear, a second gear, a third gear, a fourth gear, a first belt wheel, a transmission module(a belt), a second belt wheel, a first spring, a second spring, an active block, a passive block, a limiting wheel, and a limiting block. The active block is fixed on the fourth gear, the passive block is fixed on the terminal-phalange. The second belt wheel is fixed on the second joint-shaft, the limiting wheel is fixed on the first belt wheel, and the limiting wheel is set on the first joint-shaft. The belt is connect with the first belt wheel and the second belt wheel. The transmission ratio of this transmission relation-ship is 1. The limiting block is fixed on the base, and the limiting block touches the limiting wheel at the initial state. The second spring is connected with the limiting wheel and the base. The active block is away from the passive block, and the distance and the angle is depending on the time to switch grasping mode, which is usually a quarter of the gear's perimeter and 90 degree. The actuator is fixed in the middle-phalange, and the active gear is fixed on the output axis of the reducer. The transitional axis is set in the middle-phalange, which is set on the first joint-shaft. The transitional axis is parallel with the first joint-shaft. The active gear is meshed with the third gear, and both the third gear and the second gear is set on the transitional axis. The first spring connects the second gear and the third gear. The second gear is meshed with the first gear, and the first gear is fixed on the first joint-shaft. The fourth gear is meshed with the active gear, and the fourth gear is set on the second joint-shaft. In this structure, a torsional spring is used as the first spring, and a tension spring is used as the second 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.

B. *Grasping Process of the PASA-SEBA hand*

The grasping process is presented as Fig.3 shows, the initial state of the finger is perpendicular with the palm, and both the middle-phalange and the terminal phalange is straightened up as Fig.4(a) has shown. When the grasping motion starts, the output axis of the actuator start to rotate. Through the reducer, the power transmit to the active gear. The active gear transmit the power to third gear which set on the transitional axis and the fourth gear which set on the second joint-shaft. Through the first spring, the second gear also starts rotating. The second gear is meshed with the first gear which is fixed in the base. Therefore, when the second gear start to rotate, the middle-phalange will rotate around the first joint-shaft, towards the object. Mean-while, the fourth gear start to rotate with the active block fixed on it. Since the active gear haven't make contact with the passive block yet as Fig.3(b) has shown, the terminal-phalange, the transmission module, the first belt wheel, the second belt wheel, and the passive block will be static relative to the base. The first belt wheel only rotates around the second belt wheel, while neither the first belt wheel and the second belt wheel rotates spontaneously. In this phase, the limiting wheel touches the limiting block as Fig.5(a) has shown, and the terminal-phalange keeps straightened up as the Fig.4(b) has shown.

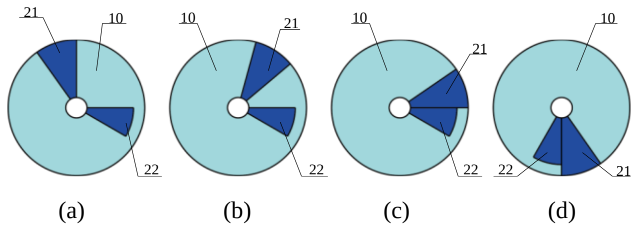

Fig. 3. The Empty-trip Mechanism

When the terminal-phalange first make contact with the object, the parallel gipping process is over. A self-adaptive grasping process is performed. When the middle-phalange first make contact with the object and the terminal-phalange has not yet make contact with the object as Fig.4(c) has shown, the first spring will deform. The power of the actuator transmit towards the fourth gear through the active gear. The active block which fixed on the fourth gear rotate a certain angle and make contact with the passive block and drive it as Fig.3(c) has shown. At the meantime, the terminal-phalange and the second belt wheel starts to rotate with the passive block. The second spring will also deform, and the limiting wheel will be away from the limiting block as Fig.5(b) has shown. This process is shown as Fig.4(d). When the terminal-phalange fully envelop the object, the whole grasping process is ended as Fig.4(e) has shown. The empty-trip mechanism is also ended as Fig.3(d) has shown. A self-adaptive grasping process is performed, and the whole parallel and self-adaptive grasping mode is finished.

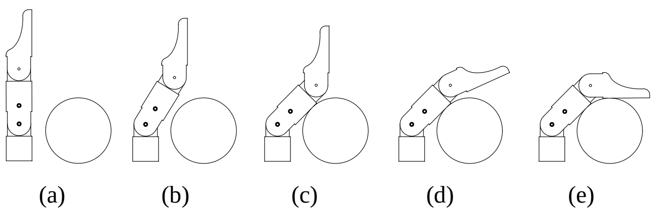

Fig. 4. The Grasping Process of PASA-SEBA finger.

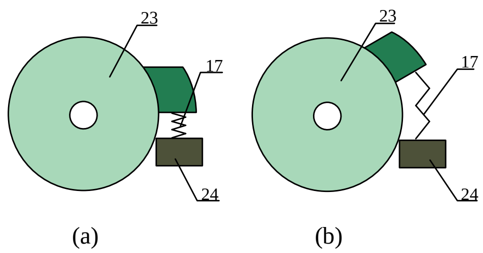

Fig. 5. The Limiting Wheel Mechanism.

IV. Force Analysis of PASA-SEBA Finger

This part focus on the grasping force distribution of PASA-SEBA finger. For the reason of simplification, the gravity force of the finger and objects, the friction between phalanges, and the transmission loss are neglected, and the contact forces are applied on points.

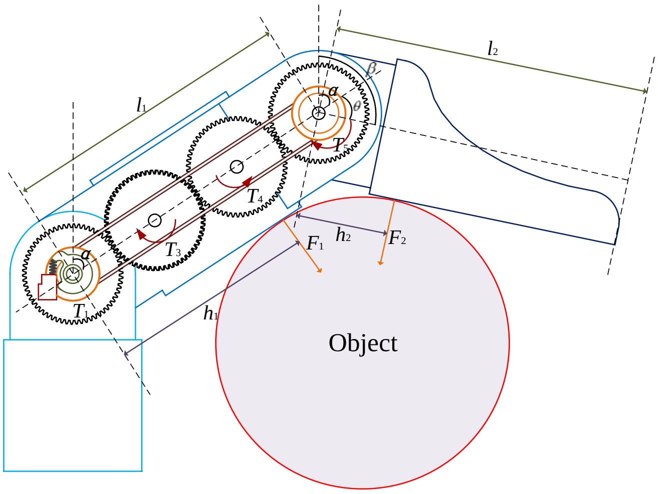

Fig. 6. Force Analysis Distribution of PASA-SEBA Finger.

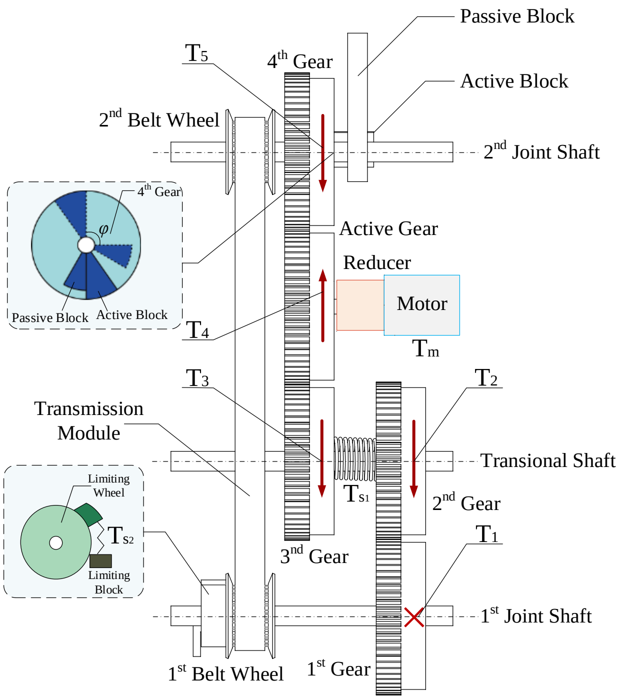

Fig. 7. Force Analysis Distribution of PASA-SEBA Mechanism.

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

φ – The initial separate angle between the active block and the passive block

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_5 – Torque of the fifth gear

T_m – Torque of the motor to the active gear
T_{s1} – Torque of the first spring
T_{s2} – Torque of the second spring
k_{s1} – The elastic coefficient of the first spring
k_{s2} – The elastic coefficient of the second spring
h_{s2} – The distance between the center of the limiting wheel and the second spring

After the parallel grasping process, when the finger fully envelopes an object, the total grasping force distribution is in an equilibrium state. Based on this characteristic, several equations can be reached as follows.

First, relative to the total torque of the motor, the torque of the motor divided into two path. The torque relationship can be drawn as follow:

$$T_m = T_3 + T_5 \tag{1}$$

Second, according to the second axis, the torque of the fifth gear also divided into two path, the second spring and the reaction force of the object. The relationship can be reached as follows:

$$T_5 = T_{S2} + F_2 \cdot h_2 \,. \tag{2}$$

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

$$T_3 = T_{s1} \,. \tag{3}$$

$$T_{s1} = k_1 \cdot (\varphi + \theta) \,. \tag{4}$$

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

$$T_{s2} = k_2 \cdot \triangle s_2 \cdot h_{s2} = k_2 \cdot {h_{s2}}^2 \cdot (\alpha + \theta) \,. \tag{5}$$

Plug equation (3) into equation (1), the torque relationship can be drawn as follows:

$$T_m = T_{s1} + T_5 \,. \tag{6}$$

Plug equation (3) (4) (5) into equation (6), the following equation can be get:

$$T_m = k_1 \cdot (\varphi + \theta) + k_2 \cdot {h_{s2}}^2 \cdot (\alpha + \theta) + F_2 \cdot h_2 \,. \tag{7}$$

Therefore, the equation of F_2 is:

$$F_2 = \frac{T_m - k_1 \cdot (\varphi + \theta) - k_2 \cdot {h_{s2}}^2 \cdot (\alpha + \theta)}{h_2} \,. \tag{8}$$

According to the second axis and the total force distribution, the torque relationship can be drawn as follows:

$$T_1 = F_1 \cdot h_1 + F_2 \cdot (h_2 + l_1 \cdot \cos\theta) \,. \tag{9}$$

$$T_1 = T_2 = T_{s1} \tag{10}$$

Plug equation (8)(10) into equation (9), the equation of F_1 can be reached as follows:

$$F_1 = \frac{k_1 \cdot (\varphi + \theta) - [T_m - k_1 \cdot (\varphi + \theta) - k_2 \cdot {h_{s2}}^2 \cdot (\alpha + \theta) \cdot (h_2 + l_1 \cdot \cos\theta) / h_2]}{h_1} \tag{11}$$

Using equation (8) and equation (11), the relationship between grasping force, rotational angle, and the arm of the force are analyzed and studied.

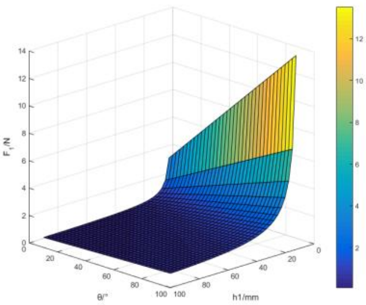

Fig. 8. First Phalange Contact-force distribution by h_1 and θ where:

$T_m = 20\mathrm{N} \cdot \mathrm{mm}, \alpha = 60^\circ, k_1 = 2\mathrm{N} \cdot \mathrm{mm}, k_2 = 1\mathrm{N} \cdot \mathrm{mm}, \varphi = 90^\circ, \eta = 95\%, h_s = 30\mathrm{mm}$

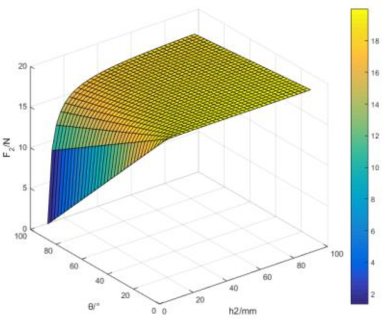

Fig. 9. Second Phalange Contact-force distribution by h_2 and θ where:

$T_m = 20\mathrm{N} \cdot \mathrm{mm}, \alpha = 60^\circ, k_1 = 1\mathrm{N} \cdot \mathrm{mm}, k_2 = 0.5\mathrm{N} \cdot \mathrm{mm}, l_1 = 80\mathrm{mm}, \varphi = 90^\circ, \eta = 95\%,$

$h_s = 20\mathrm{mm}, h_1 = 30\mathrm{mm}, h_2 = 30\mathrm{mm}$

According to Fig. 8 and Fig.9, the grasping force of the first phalange reaches maximum when the arm of the force is minimized and θ reaches maximum (90 degree). The grasping force of the second phalange reaches maximum when the arm of the force is minimized and θ reaches minimum (0 degree). This is because the two springs would consume a large amount of the torque of the motor, so the grasping force in the parallel process is bigger than the grasping force in the self-adaptive process. The multiple transmission routes have separated the torque of the motor. Overall, the PASA-SEBA robot finger is capable of grasping object effectively and stably, providing enough force to grasp an object.

V. DESIGN OF PASA-SEBA ROBOT HAND

A three-fingered gripper is designed using the PASA-SEBA finger mechanism that has already described above. The appearance of this humanoid hand is shown in Fig. 7. This robot hand consists of three PASA-SEBA robot fingers.

Each finger consists of two DOFs, two joints, and two phalanges.

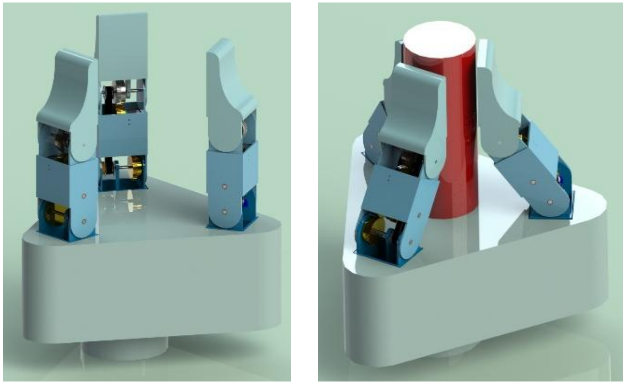

Fig. 10. PASA-SEBA Robot Hand

VI. EXPERIMENT OF PASA-SEBA ROBOT FINGER

In order to assess the performances of the PASA-SEBA finger, several grasping experiment has been conducted. Depending on the size, dimension and shape of the object, the PASA-SEBA finger can perform enveloping and pinching posture when it grasps the object as Fig.11 has shown. When the object is located on the upper side of the finger or the object is tall enough, the PASA-SEBA finger would perform parallel grasping mode and pinch the object. When the object is located on the lower side of the finger and the object is small enough, the PASA-SEBA finger would perform parallel and self-adaptive grasping mode and envelop the object. We can prove that the PASA-SEBA finger is capable of grasping object effectively and stably.

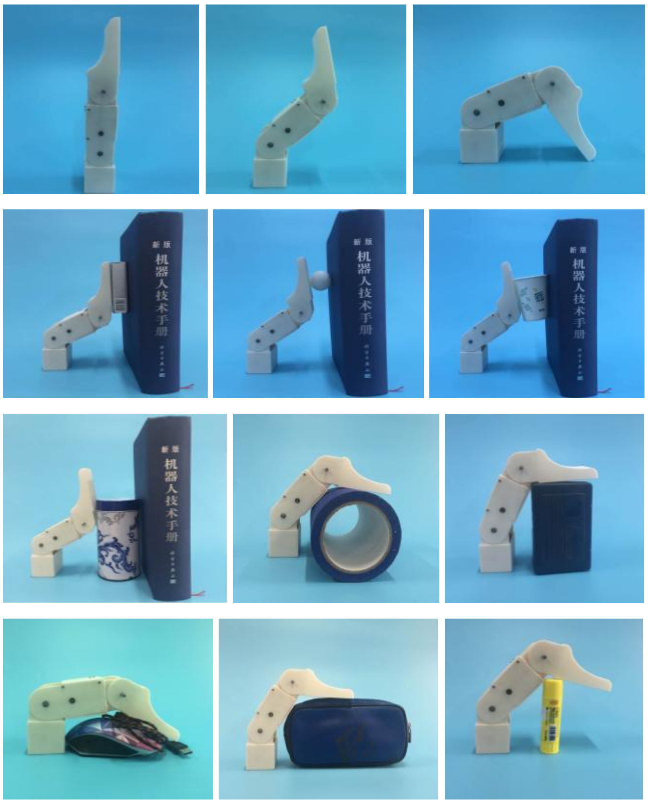

Fig. 11. Experiments of PASA-SEBA Hand

VII. CONCLUSION

This paper proposes a novel parallel and self-adaptive underactuated hand, PASA-SEBA hand. PASA-SEBA hand has 6 degrees of freedom and three fingers. Each PASA-SEBA finger consists of a seven-gear empty-trip mechanism, a built-in actuator, a belt-pulley mechanism, and two springs. These innovative mechanism allows PASA-SEBA hand to perform the hybrid parallel and self-adaptive grasping mode. The transitional axis with two gear sleeved on it, connected with a spring, and the belt-pulley system decoupled and switch the grasping mode in a creative way. It is more personified comparing to traditional underactuated robot hands. Static analysis proves its capability and credibility with the force distribution while it grasping an object. Its features of efficient, space-saving, adaptive, and concise allow it to be used in a wide arrange of applications such as industrial production, service robot, and high-risk occupation.

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