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Switchable Parallel Grasping, Coupled and Self-adaptive Robot Hand with Idle-Stroke Transmission Mechanism

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***Abstract* - This paper proposes a switchable parallel grasping, coupled and self-adaptive robot hand with idle-stroke transmission mechanism (SPCS-IS hand) which integrates the three basic grasping modes, namely parallel grasping mode, coupled grasping mode and self-adaptive grasping mode. The idle-stoke transmission mechanism (IS mechanism) is adopted into the robot hand mechanism design, so as to introduce two stages for the robot hand grasping motion. The SPCS-IS hand uses a switching device to realize the transformation between parallel grasping and coupled grasping for the first stage of grasping motion, then it will perform the self-adaptive grasping mode for the second grasping stage under the action of spring and limit device. The whole device contains only one motor and uses gear train to complete power transmission. Due to the integration of multiple grasping modes, the SPCS hand has stronger function and wider application range, especially its self-adaptability makes it can achieve envelopment for objects with different size and shape. Kinematic analysis and dynamic analysis are performed to research the adaptability and grasping ability of SPCS hand.**

Index Terms* - *Robot hand, Parallel grasping, Coupled grasping, Self-adaptive grasping, Grasping modes integration.

I. INTRODUCTION

Whether in industrial production or in daily service, it is an important task to equip the end-effector to realize operation. With the development of robots in recent years, end-effector has become the focus of research. Although the technology of industrial robots is mature and plays a great role in the production, the robot hand which is as the actuator is usually confined to a specific shape of object, and it always performs a single process for a long time, so its adaptability is not high. Under the background of flexible and intelligent production, the traditional robot hand can no longer meet the requirements of complex operation of advanced robot system.

Because of the high dexterity of human hands, it is difficult to simulate human actions as comprehensively as possible, which has been extensively studied in the field of robotics. In order to acquire the dexterity of human hands, we must first study how human hands grasp objects. Six grasping modes [1] were proposed in 1919. Through these six grasping modes, human hands can complete 80% of daily life grasping operations. As an evaluation criterion, scholars from all over the world devote themselves to the realization of these grasping modes in the research of bionic multi-fingered hand.

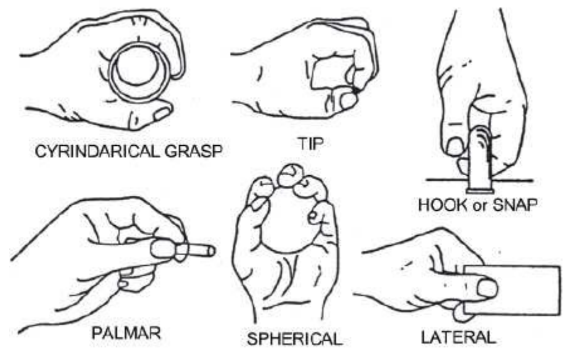


Fig. 1 Six basic grasping modes.

The traditional dexterous hands are also known as the full-drive robot hands, they rely on multi-degree-of-freedom structure and perfect sensing system to obtain abundant hand movements. Earlier examples of dexterous hands were the Utah/MIT hand [2] and Stanford-JPL hand [3] in the United States. Utah/MIT hand has four fingers, a total of 16 air-driven joint degrees of freedom, each finger joint is equipped with Hall sensor, and therefore the precise control of hand posture is realized. Japan then introduced the Gifu hands with five fingers [4, 5, 6]. The motors and controllers were placed inside the fingers and palm, totaling 20 joints and 16 degrees of freedom. The force sensors were added to effectively collect the forces feedback when grasping. In addition, the Shadow hand [7], which uses artificial muscle as transmission mechanism, the BH series full-drive hand [8, 9] of Beijing University of Aeronautics and Astronautics in China, the HIT/DLR-1 hand [10] and the HIT/DLR-2 hand [11] developed by Harbin University of Technology in cooperation with the German Aerospace Center are excellent representative works of dexterous hand.

Despite decades of development, both grasping performance and dexterity have been greatly improved, but its high cost, small grasping power, complex control and other fundamental problems still restrict the dexterous hands to enter industry and daily life. In this case, researchers began to develop a robotic hand that can meet the needs of simple daily grasping. Underactuated robotic hand came into being as the times require. Lavel University of Canada has developed

SARAH underactuated hand [12, 13], which has three fingers and three joints in each finger. The classical hand with parallel grasping mode is Robotiq hand [14] and PASA hand [15, 16] of Tsinghua University. The classical robot hand with coupled grip mode is Southampton hand [17], Manus hand [18] and Asimo hand [19, 20].

Among all the grasping modes, coupled grasping, parallel grasping and self-adaptive grasping are the three most basic grasping modes of underactuated robot hand. Based on them, researchers have explored several methods of grasping mode fusion, in order to achieve universal and stable grasping of different target objects. At present, robot hand with two grasping modes has been developed in large quantities, such as Barrett hand [21], CISA-LS hand [22] of Tsinghua University, etc. However, there are few achievements in the research of robotic hand with three or more grasping modes. The SPCS-IS hand proposed in this paper realizes coupled, parallel and self-adaptive multi-mode grasping by combining power transmission mechanism with coupling and parallel grasping transmission mechanism. According to the position, shape and size of the object to be grasped, the SPCS-IS hand can adopt a suitable mode, and the grasping range is large, the control is easy and the cost is low.

II. Design of SPCS-IS Hand

A. Idle-Stroke Transmission Mechanism

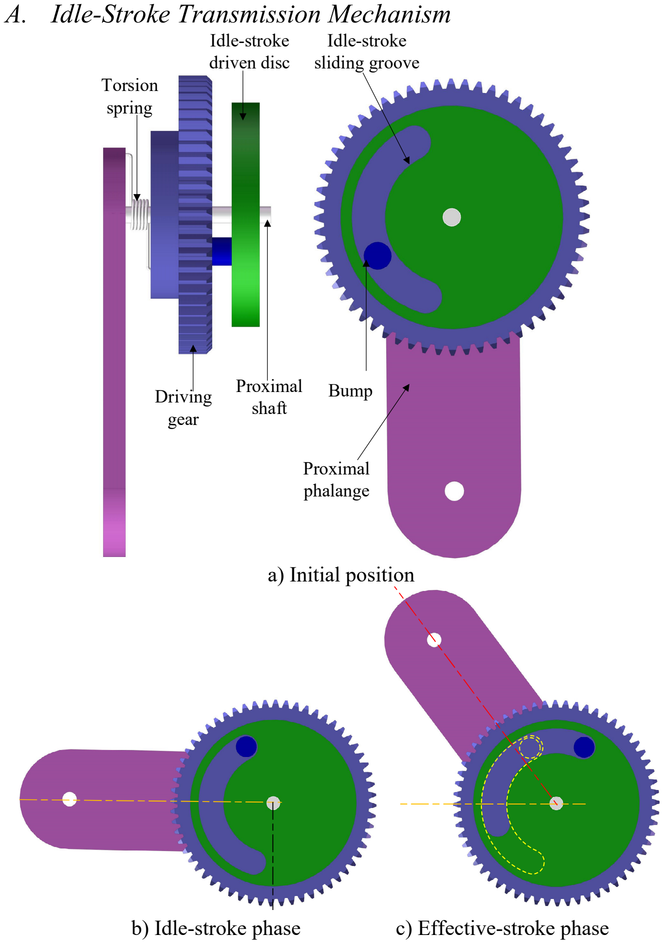


Fig. 2 The Idle-Stroke Transmission Mechanism.

Rotating idle-stroke transmission mechanism mainly uses a gear with a bump and a gear with a sliding groove to realize idle-stroke transmission. When the driving gear starts to rotate, the bump on the gear starts to rotate along the sliding groove at the same time because it is fixed on the gear, until the entire idle stroke of the sliding groove is completed, another gear is driven to rotate. That is to say the whole motion period is divided into two phase: Idle –stroke phase and effective-stroke phase.

By utilizing the multi-phase motion characteristics of the idle-stroke transmission mechanism, the SPCS-IS robot hand can easily realize the integration of various grasping modes. When the motor start to rotate, the idle-stroke transmission mechanism is in the idle-stoke phase, the SPCS-IS robot hand starts with the coupled grasping mode or parallel grasping mode. Afterwards, the SPCS-IS robot hand grasps with the self-adaptive grasping mode when the idle-stroke transmission mechanism moves to the effective-stroke phase.

B. Integration of multiple grasping modes

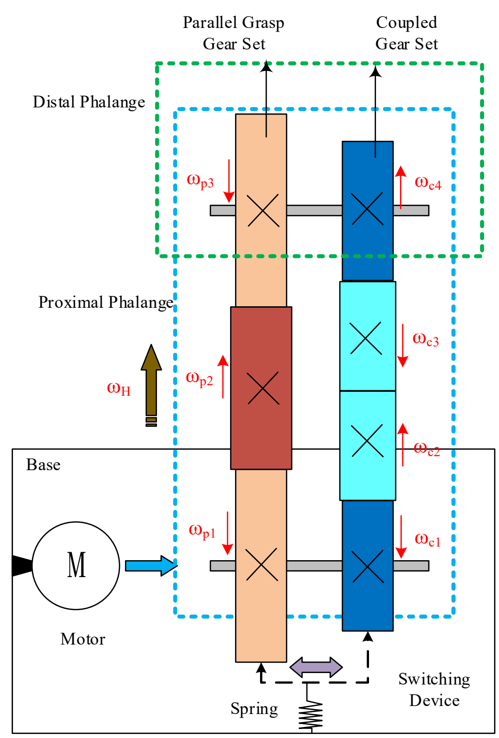


Fig. 3 Schematic diagram of SPCS mechanism.

The biggest characteristic of SPCS-IS robot hand is that it integrates three grasping modes: parallel grasping, coupled grasping and self-adaptive grasping. However, there is a certain incompatibility between parallel grasping and coupled grasping. In order to solve this conflict, a switchable parallel grasping, coupled and self-adaptive fusion mechanism is designed in this paper.

The shell of the device is composed of three parts: base, proximal phalange and distal phalange, meanwhile its interior includes two transmission chains, the parallel grasp gear set and the coupled gear set. Both transmission chains depend on the transmission principle of gear train to realize their respective functions. When the SPCS-IS robot hand works with the parallel grasping mode, the switching device will switch to the left, the bottom gear of the parallel grasping gear set will limited by spring. After the motor drives the proximal phalange to rotate , with the proximal phalange as the reference frame, the following transmission relationship exists:

$$i_{p1p3}^{H}=\frac{\omega_{p1}-\omega_{H}}{\omega_{p3}-\omega_{H}}=\frac{z_{p3}}{z_{p1}}=1 \tag{1}$$

Because gear P1 is blocked by spring, it cannot rotate, one can obtain:

$$\omega_{p1}=0\text{, so }\ \omega_{p3}=0 \tag{2}$$

That is to say, the distal phalange does not rotate relative to the base, i.e. it keeps parallel to the side of the base. Therefore, the SPCS-IS robot hand executes with parallel grasping mode.

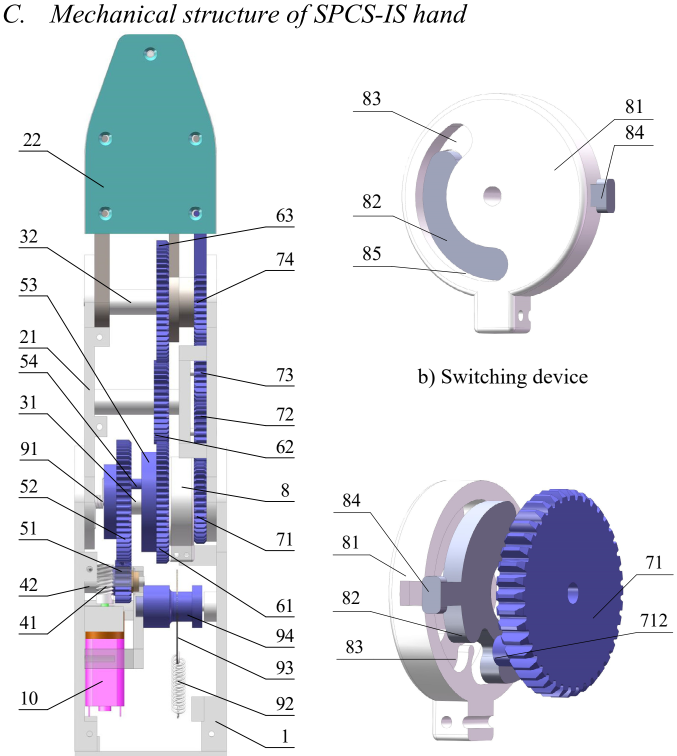
When the SPCS-IS robot hand works with the coupled grasping mode, the switching device will switch to the right. Similarly, one can obtain the following equations:

$$i_{c1c4}^{H}=\frac{\omega_{c1}-\omega_{H}}{\omega_{c4}-\omega_{H}}=-\frac{z_{c4}}{z_{c1}}=-1 \tag{3}$$

$$\omega_{c1}=0\text{, so }\ \omega_{c4}=2\omega_{H} \tag{4}$$

That is to say, the distal phalange rotates at twice the angular speed of the proximal phalange, so the motion of the distal phalange is coupled with the proximal phalange.

C. *Mechanical structure of SPCS-IS hand*



b) Switching device

a) Overall structure c) Internal structure of switching device

Fig. 4 Mechanical structure of SPCS-IS hand.

1-base; 21-proximal phalange; 22-distal phalange; 31-proximal shaft; 32-distal shaft; 41-worm; 42-worm gear; 51-driving gear; 52-driven gear; 53-idle-stroke driven disc; 54-bump; 6- parallel grasping transmission gear set; 61-63-first to third gear; 7-coupled grasping transmission gear set; 71-74-fourth and seventh gears; 8-switching device; 81-sliding rail shell; 82-slide block; 83-limit notch; 84-dial button; 85-sliding rail; 91-torsion spring; 92-tension spring; 93-tendon rope; 94-bobbin; 95-limit block; 10-motor;

According to schematic diagram of SPCS mechanism and the idle-stroke transmission mechanism mentioned above, this paper designs a switchable parallel grasping, coupled and self-adaptive robot hand with idle-stroke transmission mechanism (SPCS-IS hand). The SPCS-IS hand includes two phalanges, two joints, one motor and multiple gear transmission mechanisms. It is driven with a single motor to realize the rotation of all three degrees of freedom. Moreover, all the three grasping modes mentioned above has been integrated in SPCS-IS hand by direct series or switchable parallel connection with specific mechanism.

The exterior and structure of SPCS-IS hand has been shown in figure 4 and detailed components composition has been listed under the figure. The power provided by motor is transferred with the worm gear mechanism to the idle-stroke transmission mechanism. The driving gear of the idle-stroke transmission mechanism is connected with the proximal phalange through torsion spring, the idle-stroke driven disc is connected with the SPCS mechanism. The SPCS mechanism includes a parallel grasping transmission gear set which can realize equivalent speed and same direction transmission, a coupled transmission gear set which can realize equivalent speed and reverse transmission, a switching device and a spring.

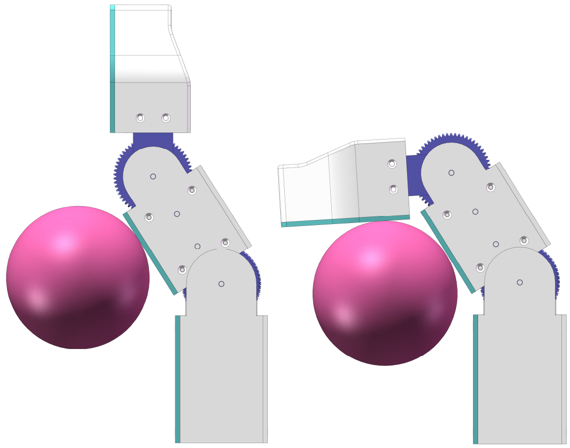
The structure of switching device has been shown in figure 4.b and c, it consists of a shell, a slide block, two limit notches, two sliding rails and a dial button. It can realize the grasping modes switching between the parallel grasping mode and coupled grasping mode when the dial button is triggered and the slide block is moving inside the shell. The lower end of the switching device is pulled by a spring through a tendon rope.

III. WORKING PRINCIPLE OF SPCS-IS HAND

The SPCS-IS hand has two alternative working modes, depending on which side of the switching device the dial button is on. If the button is dialed to the left, the bottom gear of the parallel grasping gear set will be limited by the tension spring, the SPCS-IS hand executes the parallel and self-adaptive grasping mode. In contrast, if the button is dialed to the right, the bottom gear of the coupled gear set will be limited, the SPCS-IS hand executes the coupled and self-adaptive grasping mode.

According to the structure and the design concept of the SPCS-IS hand, the working principle can be described as follows:

A. Parallel and self-adaptive grasping mode

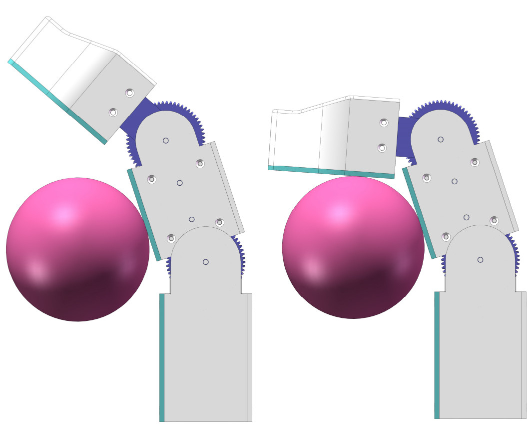


a) Parallel grasping b) Self-adaptive grasping

Fig. 5 Parallel and self-adaptive grasping mode.

The whole process for parallel and self-adaptive grasping mode includes three stages: parallel grasping stage, idle-stroke stage and self-adaptive grasping stage. When the motor start to rotate, the driving gear of the idle-stroke mechanism will drive the proximal phalange to rotate through torsion spring. Under the hindrance of the tension spring, the distal phalange keeps parallel to the side of the base. After the proximal phalange contacts the object, the proximal phalange is blocked, but the driving gear continues rotating to finish the whole idle-stroke on the driven disc, that is the so-called idle-stroke stage. During this stage, the angles of the joints remained unchanged. Then the idle-stroke transmission mechanism enters the effective-stroke stage, the bottom gear of the parallel grasping gear set will be driven and the tension spring will be elongated, the distal phalange will rotate adaptively towards until gets in touch with object.

B. Coupled and self-adaptive grasping mode



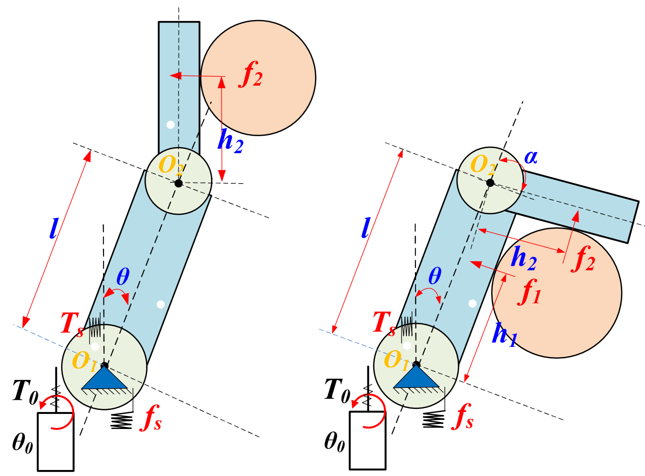
a) Coupled grasping b) Self-adaptive grasping

Fig. 6 Coupled and self-adaptive grasping mode.

The whole process for coupled and self-adaptive grasping mode also includes three stages: parallel grasping stage, idle-stroke stage and self-adaptive grasping stage. The working principle is similar to the parallel and self-adaptive grasping mode, the only difference is that during the first stage, the tension spring will limit the bottom gear of the coupled transmission gear set, so the distal phalange will coupled with the proximal phalange, which is so-called coupled grasping mode.

IV. Mechanical Analysis of SPCS-IS Hand

This section gives the mechanical analysis of SPCS-IS hand in detail to evaluate the property of it. The mechanical characteristics of the SPCS-IS robot hand in the grasping process will be analyzed based on the principle of virtual work.



a) Linearly parallel grasping b) Self-adaptive grasping

Fig. 7 Mechanical analysis of SPCS-IS hand

θ --- Rotational angle of proximal phalange, *rad*;

α --- Rotational angle of distal phalange, *rad*;

l --- Length of proximal phalange (from proximal shaft to distal shaft), mm;

h_1 --- Vertical distance from proximal shaft to action point of force on proximal phalange, *mm*;

h_2 --- Vertical distance from distal shaft to action point of force on distal phalange, *mm*;

f_1 --- Reactive force of object against proximal phalange, *N*;

f_2 --- Reactive force of object against distal phalange, *N*;

f_s --- Tension of tension spring, *N*;

T_s --- Torque of torsion spring, *N.mm*;

k_1 --- Stiffness coefficient of tension spring, *N/mm*;

k_2 --- Stiffness coefficient of torsion spring, *N.mm/rad*;

T_0 --- Torque provided by reduced motor, *N.mm*;

θ_0 --- Rotational angle of reduced motor, *rad*;

φ_0 --- Stroke angle of idle-stroke transmission mechanism, *rad*;

i --- Reduction ratio of worm gear transmission mechanism;

r --- Distance of tension force point from gear center, mm;

η --- Overall transfer efficiency;

A. Parallel grasping mode

As shown in figure 7 a), the SPCS-IS hand grasps the object with parallel grasping mode. Because the tension spring and torsion spring do not deform under the parallel grasping mode, there is no transformation of elastic potential energy in this state. One can obtain the follow equation according to the principle of virtual work:

$$-T_0 \cdot \delta\theta_0 = \vec{f}_2 \cdot \delta\vec{G}_2^{\,t} \tag{5}$$

$$\vec{f}_2 = (f_2, 0) \tag{6}$$

$$\vec{G}_2 = (l\sin\theta, l\cos\theta + h_2) \tag{7}$$

According to the kinematics relationship of the gear worm drive and the gear drive, the relationship between the motor rotational angle and rotational angle of the proximal phalange can be obtained as follows:

$$\theta = \frac{\theta_0}{i} \tag{8}$$

Thus, one can get the grasping force regarding to the proximal joint angle under parallel grasping mode.

$$-T_0 \cdot \delta\theta_0 = f_2 l\cos\theta \frac{\delta\theta_0}{i} \tag{9}$$

$$f_2 = \frac{-iT_0}{l\cos\theta} \tag{10}$$

B. Self-adaptive grasping mode

As shown in figure 7 b), if the SPCS-IS hand grasps the object with self-adaptive grasping mode, one can obtain the follow equation according to the principle of virtual work:

$$-T_0 \cdot \delta\theta_0 = [\vec{f}_1, \vec{f}_2]\begin{pmatrix} \delta\vec{G}_1^{\,t} \\ \delta\vec{G}_2^{\,t} \end{pmatrix} + T_s\delta\varphi_{Ts} + f_s\delta x_s \tag{11}$$

$$\vec{f}_1 = (-f_1\cos\theta, f_1\sin\theta) \tag{12}$$

$$\vec{f}_2 = (-f_2\cos(\theta+\alpha), f_2\sin(\theta+\alpha)) \tag{13}$$

$$\vec{G}_1 = (h_1\sin\theta, h_1\cos\theta) \tag{14}$$

$$\vec{G}_2 = (l\sin\theta + h_2\sin(\theta+\alpha), l\cos\theta + h_2\cos(\theta+\alpha)) \tag{15}$$

$$\varphi_{Ts} = \frac{\theta_0}{i} - \theta \tag{16}$$

$$T_s = k_2\varphi_{Ts} = k_2(\frac{\theta_0}{i} - \theta) \tag{17}$$

$$x_s = r(\theta+\alpha) \tag{18}$$

$$f_s = k_1 x_s = k_1 r(\theta+\alpha) \tag{19}$$

Taking derivatives on both sides of Equation (14), (15), (16) and (18), one can obtain the equations as follows:

$$\delta\vec{G}_1 = (h_1\cos\theta\cdot\delta\theta, -h_1\sin\theta\cdot\delta\theta) \tag{20}$$

$$\begin{aligned}\delta\vec{G}_2 = (&l\cos\theta\cdot\delta\theta + h_2\cos(\theta+\alpha)\cdot(\delta\theta+\delta\alpha),\\ &-l\sin\theta\cdot\delta\theta - h_2\sin(\theta+\alpha)\cdot(\delta\theta+\delta\alpha))\end{aligned} \tag{21}$$

$$\delta\varphi_{Ts} = \frac{\delta\theta_0}{i} - \delta\theta \tag{22}$$

$$\delta x_s = r(\delta\theta + \delta\alpha) \tag{23}$$

Combine the above equations, one can obtain:

$$\begin{aligned}T_0\cdot\delta\theta_0 = &\{f_1h_1 + f_2h_2 + f_2l[\cos(\theta+\alpha)\cos\theta + \sin(\theta+\alpha)\sin\theta]\}\delta\theta\\ &+ f_2h_2\delta\alpha - k_2(\frac{\theta_0}{i} - \theta)(\frac{\delta\theta_0}{i} - \delta\theta) - k_1r^2(\theta+\alpha)(\delta\theta+\delta\alpha)\end{aligned} \tag{24}$$

According to the transmission principle of the idle-stroke transmission mechanism, the joints angles have the following relationship regard with the rotational angle of reduced motor:

$$\alpha = \frac{\theta_0}{i} - \varphi_0 \tag{25}$$

Thus,

$$\{f_1h_1 + f_2h_2 + f_2l[\cos(\theta+\alpha)\cos\theta + \sin(\theta+\alpha)\sin\theta] + k_2(\alpha+\varphi_0-\theta) - k_1r^2(\theta+\alpha)\}\delta\theta - \left[k_2(\alpha+\varphi_0-\theta) + iT_0 - f_2h_2 + k_1r^2(\theta+\alpha)\right]\cdot\delta\alpha = 0 \tag{26}$$

So the grasping forces can be calculated as follows:

$$\begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \begin{pmatrix} \dfrac{2k_2}{h_1}(\alpha+\varphi_0-\theta) + \dfrac{iT_0}{h_1} + \dfrac{l\left[k_2(\alpha+\varphi_0-\theta) + iT_0 + k_1r^2(\theta+\alpha)\right][\cos(\theta+\alpha)\cos\theta + \sin(\theta+\alpha)\sin\theta]}{h_1h_2} \\ \dfrac{k_2(\alpha+\varphi_0-\theta) + iT_0 + k_1r^2(\theta+\alpha)}{h_2} \end{pmatrix} \tag{27}$$

According to equation (27), the grasping forces of the proximal phalange and the distal phalange can be obtained respectively. It can also be observed from the equation (27) that the grasping forces of the proximal phalange and the distal phalange are the functions related to the joint angles of proximal joint and distal phalange for the SPCS-IS robot hand whose the components, such as motor, reducer, gear, worm, worm gear, tension spring and torsion spring are determined.

According to the actual dimension and components selection of SPCS-IS robot hand, some necessary value can be measured as follows:

φ_0=120°; l=100*mm*; h_1=60*mm*; h_2=30*mm*; k_1=0.5*N/mm*; k_1=200*N.mm/rad*; r=30*mm*; T_0=800*N.mm*; i=20.

Taking the above parameters into Equation (27), one can draw the distribution diagram of grasping forces with regard to the joint angles.

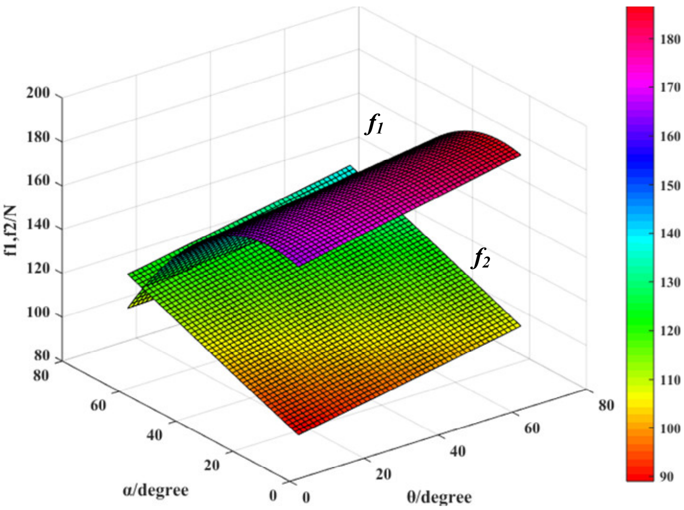


Fig.8 Grasping forces of SPCS-IS hand

From figure 8, we can concluded that, the grasping force of the proximal phalange decreases with the increase of the distal joint angle, and the grasping force of the distal phalange increases with the increase of the proximal joint angle and distal joint angle. Both grasping forces are between 80N and 180 N, they are sufficient for the grasping motion of daily objects.

Ⅴ. Conclusion

This paper proposes a new type switchable parallel grasping, coupled and self-adaptive robot hand with idle-stroke transmission mechanism (SPCS-IS hand). It integrates the three basic grasping modes, namely parallel grasping mode, coupled grasping mode and self-adaptive grasping mode. The structure of the whole robot hand is very concise, but its function is complete. The idle-stroke transmission mechanism and SPCS mechanism developed for the SPCS-IS hand solves the difficult problem of multi-mode fusion ingeniously. Based on the principle of virtual work, the mechanical analysis shows that the grasping forces of both phalanges are sufficient for grasping normal objects.

Acknowledgment

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References

[1] Schlesinger I G: Der Mechanische Aufbau der Künstlichen Glieder, Ersatzglieder und Arbeitshilfen: Springer, 1919: 321-661.

[2] Jacobsen, S., Iversen E., Knutti D., et al. Design of the Utah/MIT Dexterous Hand. IEEE Int. Conf. Robotics and Automation, Los Alamitos, Calif., p. 1520-1532, 1986.

[3] Salisbury, J.K., and Craig, J.J., Articulated Hands: Force Control and Kinematic Issues. The Int. J. of Robotics Research, Vol.1, No.1, p. 4-17, 1982.

[4] Mouri, T., Kawasaki, H., Yoshikawa, K., et al. Anthropomorphic robot hand: Gifu hand III. Iccas, 2002, 2001:212-213.

[5] Kawasaki, H., Komatsu, T., Uchiyama, K. Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II. IEEE/ASME Transactions on Mechatronics, 2002, 7(3):296-303.

[6] Kawasaki, H., Komatsu, T. Mechanism design of anthropomorphic robot hand: Gifu Hand I. JRM, 11(4), 269–273.

[7] Tuffield, P., Elias, H. The Shadow Robot Mimics Human Actions. Industrial Robot: An Int. J., 2003, 30(1), pp: 55-60.

[8] You song, Zhu guangchao, Arm-hand integration System for intelligent robot. The Journal of Robotics technology and application, Vol. 2. pp. 21-24. 1999.

[9] Shang Xisheng, Guo Weidong, Zhan Hao, etc, Grasp Planning and Realization of BH-4 Dexterous Hand. Robot, 2000, 22(7): 608-612 (in Chinese).

[10] Liu, H., Meusel, P., Hirzinger, G., et al. The modular multisensory DLR-HIT-Hand: hardware and software architecture. IEEE/ASME transactions on mechatronics, 2008, 13(4): 461-469.

[11] Liu, H., Wu, K., Meusel, P., et al. Multisensory five-finger dexterous hand: The DLR/HIT Hand II. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Nice, Sept, 2008: 3692-3697.

[12] Laliberté, T., Gosselin, C. M. Underactuation in space robotic hands. Proc. int. symp. artif. intell. robot. autom. space, 2001.

[13] Martin, E., Desbiens, A. L., Lalibert E, T., et al. SARAH hand used for space operations on STVF robot. 2004 Int. Conf. on Intelligent Manipulation and Grasping, Genoa, Italy, July 1-2, 2004.

[14] Allen Demers, L. A., Lefrançois, S., Jobin, J. P. Gripper having a two degree of freedom underactuated mechanical finger for encompassing and pinch grasping: US, US8973958 B2. 2015-3-10.

[15] Liang, D. Y., Song, J., Zhang, W. Z., et al. PASA Hand: A novel parallel and self-adaptive underactuated hand with gear-link mechanisms. Int. Robotics and Applications, Icira 2016, Pt I, 2016, 9834: 134-146.

[16] Liang, D., Zhang, W., Sun, Z., et al. PASA finger: A novel parallel and self-adaptive underactuated finger with pinching and enveloping grasp. 2015 IEEE Int. Conf. on Robotics and Biomimetic (Robio), 1323-1328.

[17] Dubey, V. N., Crowder, R. M. Grasping and control issues in adaptive end effectors. ASME Design Engineering Technical Conf. and Computers and Information in Engineering Conf., New York, May, 2004:1-9.

[18] Pons, J. L., Rocon, E., Ceres, R., et al. The manus-hand dexterous robotics upper limb prothesis: Mechanical and Manipulation Aspects. Autonomous Robots, 2004, 16(1): 143-163.

[19] ASIMO: The world's most advanced humanoid robot. [2014-01-01]. http://asimo.honda.com/asimo-function/arms-hands/.

[20] Stansfield, S. A. Robotic grasping of unknown objects: A knowledge-based approach. Int. J. on Robotics Research, 1991, 10(4): 314-325.

[21] Townsend W. The BarrettHand grasper – programmably flexible part handling and assembly. Industrial Robot An International Journal, 2000, Vol. 27 No. 3, pp. 181-188.

[22] Liu S, Zhang W, Sun J. A coupled and indirectly self-adaptive under-actuated hand with double-linkage-slider mechanism. Industrial Robot: the international journal of robotics research and application, 2019, Vol. 46 No. 5, pp. 660-671.