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Design of a Highly Compliant Underactuated Prosthetic Hand*

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***Abstract*— This paper presents a highly compliant prosthetic hand based on a novel synergy mechanism. The prosthetic hand consists of a synergy mechanism, four fingers and one thumb. The synergy mechanism can transmit the power from two motors to four fingers. It can effectively reduce the number of motors. At the same time, it makes the prosthetic hand have excellent dexterity. The underactuated finger has three joints with two DOF. It has two main motion modes: coupled motion in free space and self-adaptive motion when contacting with the object, which can mimic the human finger as much as possible. The thumb uses one motor to drive the two flexion-extension joints and uses a manual switch to drive the abduction-adduction joint, which can reduce the number of motors and the cost efficiently. The performance evaluation is given to demonstrate the comprehensive performance in terms of the versatility, compliance, sensing, size, weight and cost of the proposed design.**

***Index Terms*— Underactuation, Prosthetic hand, Robotic hand, Coupled-adaptive, Synergy mechanism.**

I. INTRODUCTION

It is well known that the human hand is the most dexterous tool for human being to perform complex task and activities of daily living (ADLs). Furthermore, it is also a significant human organ to complete sign language, which plays an important function in nonverbal communication.

To restore the natural hand function to disabled people who have suffered upper-limb amputations, scientists put a lot of energy to develop myoelectric prosthetic hands. Through decades of development, several advanced prosthetic hands have emerged on the commercial market [1], such as the Vincent Evolution hand (Vincent Systems), i-Limb quantum hand (Touch Bionics), Bebionic hand (RSL Steeper) and Luke arm (DEKA Research & Development Corporation) [2]. These commercially available prosthetic hands further improved the appearance. However, these hands cannot be widely used by the amputees, because of the high costs, and the lacking of sensory information like the natural hands.

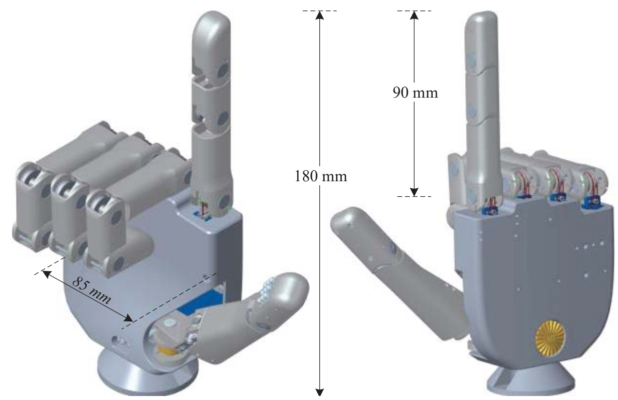

Fig. 1. The highly compliant underactuated hand.

Underactuated mechanism, whose number of actuators is less than the degrees of freedom, is an usefulness technique to increase the inherent compliance, and reduce the structure complexity of the prosthetic hand [3]. Hence, it is widely used in prosthesis design. To date, large numbers of notable prosthetic hands with this kind of mechanism have been developed [4], such as the MANUS Hand [5], SmartHand [6], CyberHand [7] and UT Hand [8]. Particular, the hands described in Ref. [9], [10] utilize a single actuator to drive all the joints through a multi-way differential mechanism between the fingers, to improve their adaptive grasping capabilities while keeping the cost as low as possible. The hands described in [11]–[13] try to take advantage from the idea of synergies, which is an effective design method to decrease the number of actuators, and then simplify the hand structure and reduce the costs. Particular, to combine the advantages of coupled hands and self-adaptive hands, the Tsinghua university proposed a series of coupled-adaptive hands [14], [15]. This type of underactuated hands can execute coupled motion like the human being before it contacts object, and then execute self-adaptive motion after it is restrained by the object. Despite the fact that the underactuated bring many advantages for the underactuated hand, but few of these hands can achieve the balance between the versatility, compliance, sensing, modularity, robustness, size, weight and cost.

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Overall, the prosthetic hand should have the similar appearance and grasping capability as the human counterpart, since it plays a critical role for helping the amputees to live an active life. To address these problems, we extend our previous work [16], [17] and propose a highly compliant prosthetic hand based on a novel synergy mechanism. As shown in Fig.1 and Fig. 2, it consists of a synergy mechanism, four identical underactuated fingers and one thumb. The underactuated finger can perform coupled motion and self-adaptive motion like the human finger. The thumb uses one motor to drive the two flexion-extension joints and uses a manual switch to drive the abduction-adduction joint. This kind configuration makes the underactuated hand have a comprehensive performance in terms of the versatility, compliance, sensing, size, weight and cost.

The rest of the paper is organized as follows: Section II describes the design requirements of the underactuated prosthetic hand. Section III presents the design methods of the synergy mechanism, underactuated finger and the thumb in detail. The performance evaluation of the prosthetic hand is analyzed in Section IV, and the conclusion is discussed in Section V.

II. Design Requirement

Since the prosthetic hand is the significant tool for amputees to perform general activities of daily living, it must be as similar as possible to the native hand. Based on the collection of studies on human hand anatomy and postural synergies, several reasonable design requirements are as follows:

- Underactuation: As described, the adaptive mechanism can effectively reduce the number of actuators and allow the fingers to adapt to the shape of a grasped object to increase the contact points between the prosthetic hand and object.
- Anthropomorphism: The prosthetic hand should have four fingers with three joints and one thumb. Since the reach-to-grasp movement is very important, the underactuated finger should have this dynamic character to restore the motion function of the human hands perfectly.
- Functionality: The prosthetic hand should provide enough fingertip forces (usually more than 10 N) and speeds (finger closing in less than 1 s) . Besides, it should provide the basic grasps and gestures of ADLs which described in Ref. [18]. In addition, the prosthetic hand should have the senses of position and force of the environment.
- Practicality: The prosthetic hand should have a self-locking ability. The use of self-locking mechanism allows for holding the finger position without driving the motor for prolonged periods. All the actuators and motion controllers should be embedded in the hand.

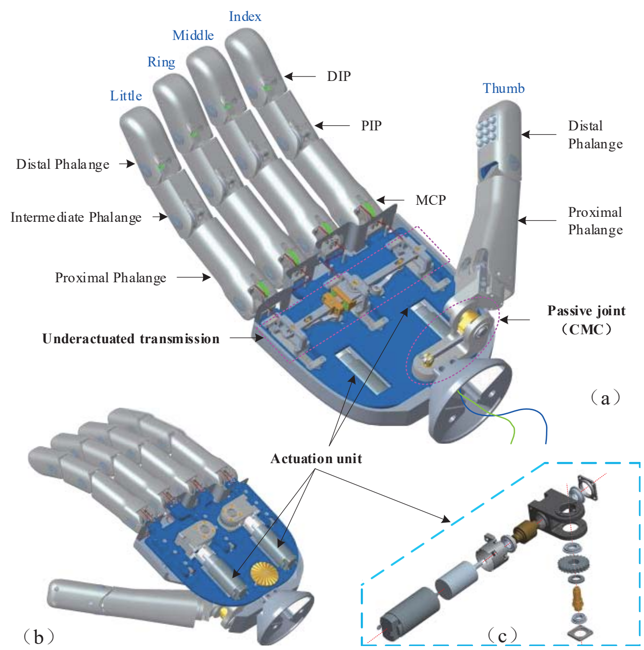

Fig. 2. Composition of the prosthetic hand: (a) The components of the prosthetic hand (All the components are mounted in the blue base of the palm); (b) The layout of the modular actuation units; (c) The components of the modular actuation units

III. Design of the Underactuated Prosthetic Hand

According to the reasonable design requirements discussed before, this section will describe the design method of the versatile underactuated prosthetic hand detailly.

As shown in Fig.1 and Fig.2, the prosthetic hand has an equivalent human-like appearance. It is 180 mm in length, 85 mm in width, and about 500 g in weight. The hand consists of four identical fingers with three joints each and one thumb with three joints. The four fingers are driven by two actuation units through a set of synergy mechanism embedded in the palm, as shown in Fig.2(a),(b). The two flexion-extension joints of the thumb are driven by one micro-motor embedded in the proximal phalanx. The adduction/abduction joint of the thumb is a passive joint which actuated by a manual switch mounted in palm. The switch makes the thumb has five different adduction/abduction positions.

The actuation unit is a modular system, which includes a DC motor (Faulhaber series 1224N-006SR, no-load speed 13800 min-1, stall torque 5.31mNm), a planetary gearhead (reduction ratio 16:1), and a set of worm gearing (reduction ratio 25:1) for self-locking. The composition and position of the modular actuation units of the finger are illustrated in Fig.2(b),(c).

The design methods of the synergy mechanism, underactuated fingers and thumb will be intruduced detailly.

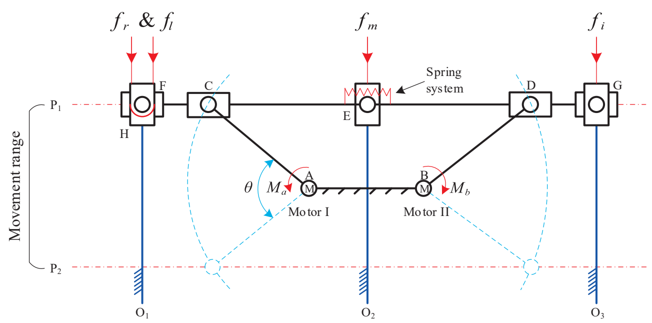

Fig. 3. The schematic diagram of the synergy mechanism.(The f_i,f_m,f_r and f_l are the force of the tendon)

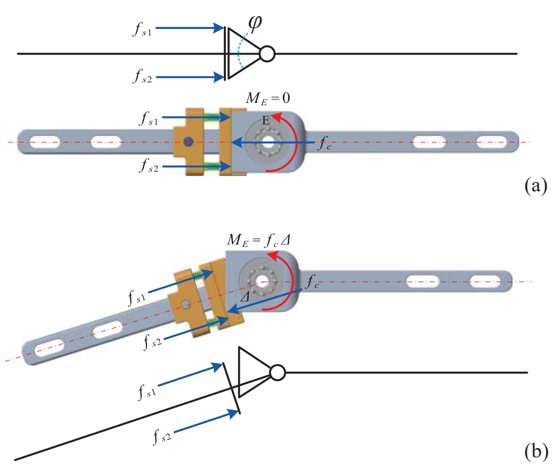

Fig. 4. The illustration of the transfer bars and the elastic joint. (a) The initial position of the elastic joint, where the $\phi = 0$ and $M_E = 0$;(b) The differential position.

A. Synergy mechanism

In order to reduce the number of the actuators to reduce the size, weight and cost of the prosthetic hand, this paper proposes a novel synergy mechanism to actuate the four fingers with only two motors. As shown in Fig. 3, the transmission is designed as a symmetrical structure, which can simplify the underactuated system efficiently. A and B are the motor positions. C, D, E, F and G are sliding blocks. H is the pulley connected to the sliding block F. O_1, O_2 and O_3 are guides fixed on the palm base. P_1 is the up limit position of the sliding blocks. P_2 is the lower limit position of the sliding blocks. AC and BD are the driving bars, EF and EG are the transfer bars. Particular, the joint between the EF and EG is an elastic rotation joint E, which has an initial torque to keep the transmission system stable at the normal position.

The index, middle,ring finger and the little finger are actuated by the three sliding blocks E, F, G and the pulley H through the tendons respectively. The three sliding blocks are the outputs of the synergy mechanism. The synergy

TABLE I

DESIGN PARAMETERS OF THE SYNERGY MECHANISM

Item	AB	AC	O_1O_2	P_1P_2	θ
Digital	6mm	27mm	36mm	10mm	38.94°

mechanism has two input blocks C and D, which are linking to the driven bars AC and BD respectively. The AC and BD are connected to the actuation units through the output shafts A and B, as shown in Fig.2.

Main design parameters of the underactuated transmission include the length variables AC, BD, EF, EG, and the position variables AB, as described in Fig.3. The design goals include i) minimize the torque of the joint E in free space, ii) minimize the size of the transmission mechanism and iii) improve efficiency of the transmission. Since the transmission system is a symmetrical structure, it has the equations $AC = BD, EF = EG, O_1O_2 = O_2O_3, AO_2 = O_2B, P_1A = AP_2$. The design parameters of the synergy mechanism are as Table.I, where θ is the maximal rotation angle of the driving bar.

When the synergy mechanism generate the differential outputs in adaptive pattern, the mechanical model of the joint E is as Fig.4. The torque of the elastic joint could be derived as in Eq.(1) and Eq.(2).

$$M_0 = kx_0 V \tan\frac{\varphi}{2} \tag{1}$$

$$M_1 = \left(\frac{M_0}{V\tan\frac{\varphi}{2}} + kV\left(\frac{\sin\left(\frac{\varphi}{2}-\phi\right)}{\cos\frac{\varphi}{2}} - 1\right)\right)\frac{V\sin\left(\frac{\varphi}{2}-\phi\right)}{\cos\frac{\varphi}{2}} \tag{2}$$

where φ is the size of the head of the transfer bar EG, as shown in Fig.4(a), M_0 is the initial torque of the joint E, M_1 is the optional torque of the joint E, k is stiffness of the springs, x_0 is the initial compression of the springs, $\phi$is the rotation angle between the transfer bar EF and EG, V is the offset between the rotation center of the transfer bar EG and the sliding block on the transfer bar EF.

According to the function of the spring, we select the design parameters of the elastic joint is as Table (II). According to the Eq.(2) and Table II, the torque of the elastic joint could be obtained. As shown in Fig.5, when the rotation angle between the transfer bar EF and EG is $0° \sim 7°$, the torque M_1 remains basically constant. When rotation angle

TABLE II

DESIGN PARAMETERS OF THE ELASTIC JOINT

Item	V	θ	k	kx_0
Digital	6mm	40°	0.8N/mm	2.78N

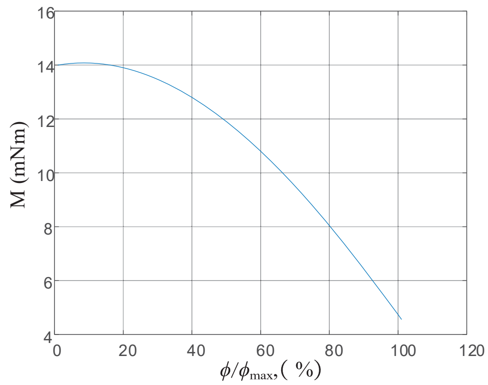

Fig. 5. The negative stiffness characteristic of the elastic joint.

between the transfer bar EF and EG continue to increase, the torque M_1 becomes smaller, which showing the negative stiffness characteristic of the elastic joint. This kind structure with negative stiffness characteristic could reduce the energy loss. It also can be used in many other scenarios.

B. Underactuated finger

As described in Section I, adaptive mechanism allows the anthropomorphic finger to adapt to the shape of a grasped object to increase the contact points between the hand and object. It is appropriate to design an underactuated anthropomorphic finger with three phalanges and two degrees of freedom, since it leads to more efficient shape adaptation.

Since the coupled finger can produce the humanoid motion, and the adaptive finger can produce the compliant grasping, this paper combines the coupled and the adaptive concept, and proposes a novel design method of the underactuated finger. As shown in Fig.6, the underactuated finger consists

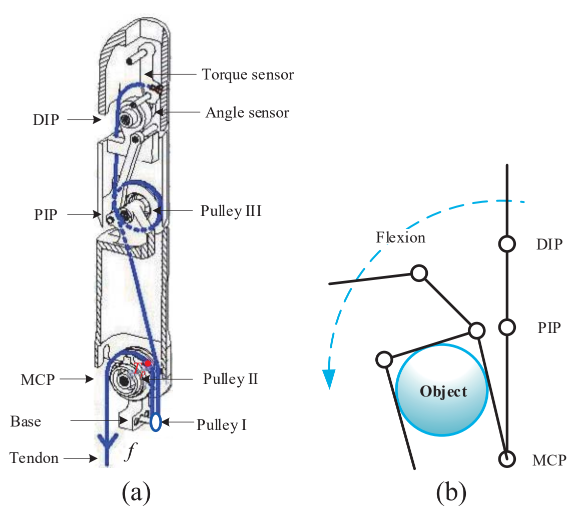

Fig. 6. Underactuated finger. (a) The components of the finger; (b) The coupled-adaptive motion model of the underactuated finger.

of one base and three phalanges: proximal phalanx(PP), medial phalanx (MP) and distal phalanx (DP). There are three joints in the connections of phalanges, which called met-metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP) and distal interphalangeal joint (DIP). The three joints are actuated by a steel tendon. In particular, the PIP joint is driven by DIP joint through a coupled linkage. The transmission ratio between DIP and PIP is approximate 2:3.

In addition, the underactuated finger has three pulleys, one torque sensor and one angle sensor. The pulley II is set on the MCP joint. It fixed on the proximal phalanx through a spring, at the same time , fixed on the tendon on point Tp. The pulley III is set on the PIP joint, and can rotation around the PIP axis. The torque sensor is fixed on the DIP joint. When the force acts on the tendon, the tendon will drives the three joints to rotate at the same time. If the medial phalanx or distal phalanx touches the object first, the finger finishes the grasping. If the proximal phalanx touches the object first, the PIP and DIP joints will continue rotating until one of them touches the object, as show in Fig.6(b).

C. Thumb

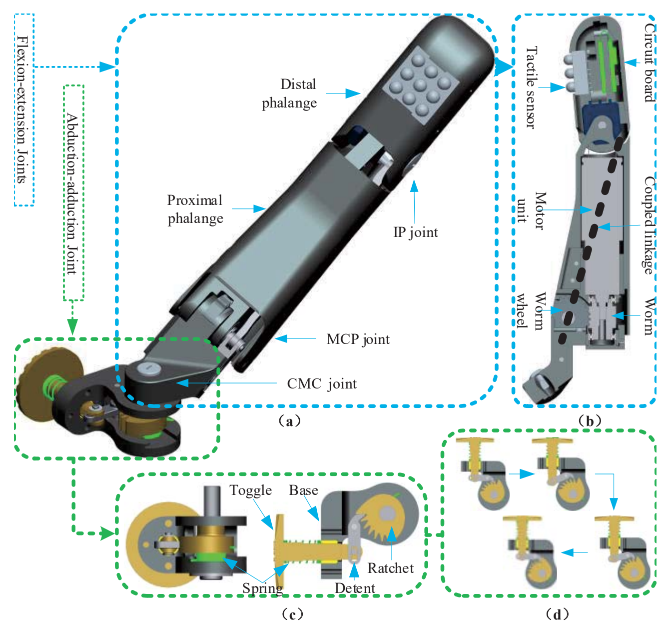

Fig. 7. Thumb mechanism. (a) The thumb appearance; (b) The components of the thumb; (c) The components of the CMC joint of the thumb; (d) The mechanism of the passive joint.

The components of the thumb are as shown in Fig. 7. Different from the underactuated fingers, it not only has IP joint and MCP joints, but also has one extra special joint (CMC joint) that can perform abduction-adduction motion like the human thumb. In order to simplify the structure and reduce the cost, the MCP joint is designed to be actuated by one motor embed in the proximal phalange. The IP joint is driven by the MCP joint by a set of four-bar mechanism.

Particular, the CMC joint is a manual joint, as shown in Fig. 7(c). The use of customized ratchet and spring allow the thumb to stay in different abduction-adduction positions. When the amputee press the toggle on the back of the hand with the other hand, the CMC joint will return to the initial position, as shown in Fig. 7(d). The thumb also has one tactile sensor embedded in the fingertip and one angle sensor embedded in the IP joint to guarantee the precision and robust grasping.

IV. Performance Evaluation

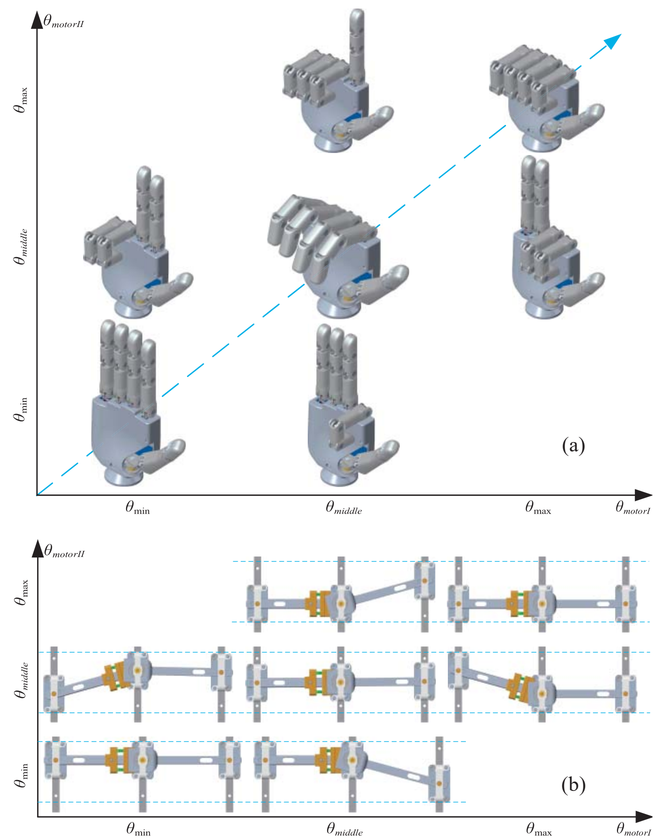

Fig. 8. The synergy mechanism status in different grasping model (Horizontal axis is the angle of actuation unit I; Vertical axis is the angle of actuation unit II).(a) Different grasping model; (b) Different status of the transmission (the blue dotted line represent the limit position of the blocks).

In order to evaluate the grasping performance of the proposed prosthetic hand with the novel synergic mechanism in this paper, a group of grasping experiments is simulated by the PTC software. As shown in Fig.8, different combinations of the rotation angle of the two motors can generate different transmission status (Fig.8(b)) which can be mapped to different hand grasping motions (Fig.8(a)). Particular, the frame in the Fig.8 represents the workspace of the underactuated prosthetic hand. The blue diagonal in the frame represent that both actuation units have the same output angle, which can drive the fore fingers to rotate at the same speed. The simulation in Fig.8 demonstrates that the highly compliant prosthetic hand has a high dexterity and can perform various graspig grastures by using the synergy mechanism.

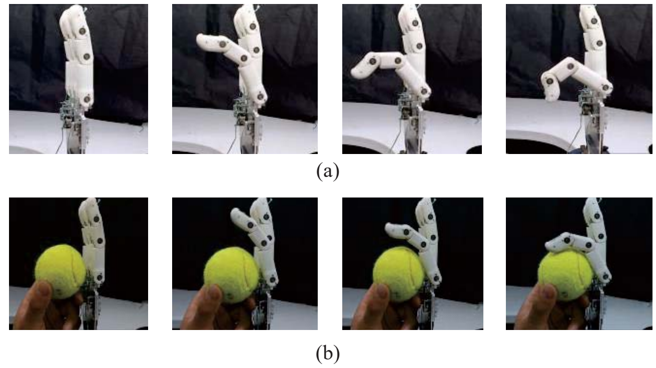

Fig. 9. The grasping performance of the underactuated finger.(a) Coupled motion of the underactuated finger in freespace; (b) Adaptive motion of the underactuated finger in workspace;

In addition, a 3D printed finger model is manufactured to evaluate the anthromorphic kinematics. Fig.9 shows that the coupled-adaptive finger can perform coupled motion in freespace like the human hand. At the same time, it has an excellent adaptability in workspace.

V. Conclusions

In this paper, a highly compliant prosthetic hand based on a novel synergy mechanism is developed. It has four modular fingers and one thumb. The finger has three joints with two DOF. It can perform coupled motion in free space and self-adaptive motion when contacting with the object, which can mimic the human finger as much as possible. The thumb uses one motor to drive the two flexion-extension joints and uses a manual switch to drive the abduction-adduction joint, which can reduce the number of motors and the cost efficiently. The synergy mechanism can transmit the power from two motors to four fingers. It can effectively reduce the number of motors. At the same time, it makes the prosthetic hand have excellent dexterity. The performance evaluation is given to demonstrate the comprehensive performance in terms of the versatility, compliance, sensing, size, weight and cost of the proposed design. At the end, simulations and experiments demonstrate that the proposed hand has excellent dexterity and adaptability. Particular, the elastic joint in the synergic mechanism has a negative stiffness characteristic, which can provide stability and save power at the same time. The design concept of negative stiffness mechanism also can be used in many other scenarios.

In the future work, the other prosthetic hand components will be fully manufactured, to evaluate the grasping performance of the prosthetic hand in the daily living environment. In addition, the EMG control signal and the vibration feedback will be integrated into this prosthetic hand, which will convery a sense of touch back to user to better manipulate the prosthetic hand. Furthermore, the efficient control strategies based on multi-sensor and the EMG control strategies for underactuated prosthetic hand will be investigated.

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