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A Novel Hedgehog-Inspired Pin-Array Robot Hand with Multiple Magnetic Pins for Adaptive Grasping

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Abstract. Advanced service robots and flexible production lines demand more universal grippers than conventional ones. In response to the deficiencies of Omnigripper proposed by previous scholars, this paper proposes a novel hedgehog-inspired robot hand (HIPA Hand) with multiple magnetic pins for general self-adaptive grasping. The HIPA hand utilizes electromagnets as the main driving part and the motor as another driving part. HIPA hand can grasp the object of different sizes and shapes. The theoretical analysis and simulation experimental results show that this device has a special advantage of quick grasping and big grasping force compared with the traditional pin-array grippers.

Keywords: Robot hand · Universal gripper · Pin-array · Self-adaptive grasping

1 Introduction

The manipulator, which has a wide range of applications in many fields, is the most important actuator and the interaction link between the robot and the outside world.

To achieve grasping, industrial gripper is firstly proposed. For example, SCHUNK [1] makes the industrial gripper with two relative motion parts, which has the advantages of low cost and easy control, but the reliability of the industrial gripper is poor.

Some dexterous hand adopts the method of highly imitated human hand mechanism to realize the multi-direction grasping of the target object. The grasping stability is obviously improved, but each finger is equipped with multiple joints and sensors, resulting in high cost and complicated control system [2–4], such as Utah/MIT Dexterous Hand [5], Gifu Hand II [6], the Shadow Hand, Stanford/JPL Hand [7] and so on.

The bionic manipulator Octopus Gripper [8] recently launched by FESTO, has good adaptability, that is, it can grasp the object without knowing what shape and size the objects are before fetching. This automatic adaptation to the shape and size of an object allows the manipulator to grasp objects more widely.

For self-adaption, there are some grippers with pin-array has been proposed. This type of gripper can be traced back to the Omnigripper [9] proposed by British scholars in the 1980s, as shown in Fig. 1. The Omnigripper has two sets of pin-array, each pin-array consists of several slidable pins. When this gripper grasping object, the two sets

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of pin-array adapt to the shape of the object from the vertical direction. After adaption, the two sets of pin-array move together to form grasping force from two sides of the object. The Omnigripper has a good ability of self-adaption and large grasping force, but it has some shortcomings:

(i) Over-simple grasping method. When the device exerts a grasping force on the target object, the grasping force can only be along the direction where the two groups of pin-array together, and cannot achieve multi-direction grasping, thus the grasping effect is poor.

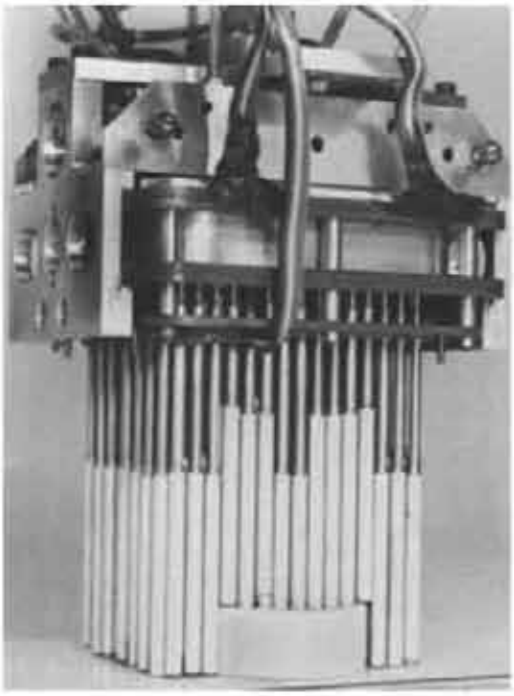


Fig. 1. Universal grasping device Omnigripper

(ii) For a long strip placed in a particular direction, the grip fails.
(iii) The complex structure and high energy consumption. The device has 2 groups of pin clusters, 2 supporting pieces, 1 set of linear guide, 2 sliders, drive, drive mechanism and so on. The structure is relatively complex, and it is of high energy consumption to make one group of heavy pins clusters with many long poles move together.
(iv) Poor reliability in long-term use. All the long pins and chutes are exposed in the working environment, and the dust is absorbed and concentrated in the long pins and chutes, which greatly affects the sliding effect of the long pins in the base and even causes failure.

In order to solve the shortcomings of Omnigripper, scholars from Tsinghua University in China proposed some pin-array grippers [10–13]. These pin-array grippers can achieve good adaptive crawling.

While most of these pin-array grippers are driving by motors or negative pressure, which has the shortcoming of slow grasping. In order to achieve faster grabbing, this paper proposes a new type of pin-array gripper driven by an electromagnet.

2 Hedgehog-Inspired Pin-Array Robot Hand

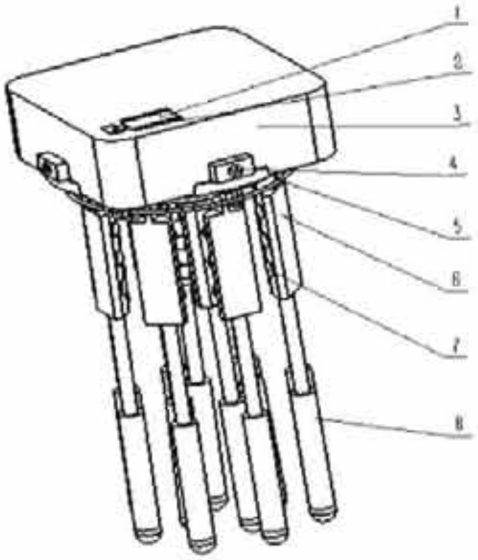
The device uses the combination of motor, electromagnet, oscillating pin, sliding tube and so on to realize the spatial discrete adaptive grasping function, as shown in Fig. 2. The device has the following advantages:

(i) It has sensitive movement and adjustable grip force.
(ii) It can adapt itself to the shape and size of the object in both horizontal and vertical directions, and it has large grasping force, high reliability, simple structure, and low cost.
(iii) The sliding tube has the ability of radial swing and wide grasping range.
(iv) It is able to grab multiple objects at the same time, and it is of simple structure and low energy consumption.

Fig. 2. Design of hedgehog-inspired pin-array robot hand

2.1 Composition Principle

The component structure of the device is as shown in Fig. 3, including the base, hemispheric parts, motors, magnetic driving pins, and other components. According to the structural function, it can be divided into two major parts: the executive part and the control part, which will be discussed in Sects. 2.2 and 2.3.



1- Motor, 2-Reel, 3-Base, 4-Bolt, 5-Elastic cord, 6-Oscillating pin, 7- Electromagnet, 8-Slide bar.

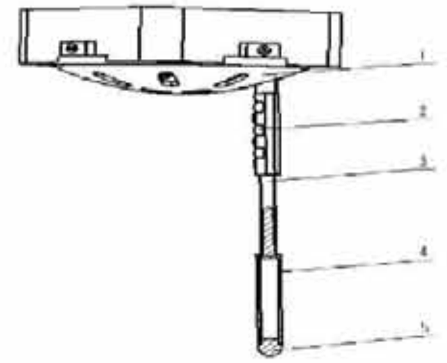
Fig. 3. Schematic of the hedgehog-inspired pin-array robot hand structure

2.2 Executive Part

The magnetic drive pin is the actuating mechanism of the Hedgehog Imitation Magnetic Drive Pin Ball Adaptive Robot Hand Device. The electromagnet is its main driving element, and the power supply makes it attract (repel) each other, thus making the magnetic drive pin gather (disperse) in the radial direction. In addition, the motor power source and elastic cord are combined to make up for the insufficient attraction of electromagnet.

Magnetic drive pin consists of an electromagnet, oscillating pin, rubber head, and sliding tube, as is shown in Fig. 4(a). Among them, the oscillating pin is hinged on the base, as is shown in Fig. 4(b), and it can swing in the radial direction. Meanwhile, the sliding tube can slide along the axis of the guide bar under the action of the reset spring, so that it can adapt to the shape and size of the object both horizontally and vertically. In order to reduce the friction of the sliding tube along the direction of the oscillating pin, the guide rod adopts a relatively smooth PTFE rod, which saves the bearing and reduces the volume of cluster-hand.

The execution of the auxiliary drive part mainly consists of the motor and elastic cord, as is shown in Figs. 3 and 4(b). The motor is connected with an elastic cord by winding wheel, with the elastic cord playing the role of tightening slide tube, which makes the outer slide tube gather towards the center, so as to achieve the purpose of



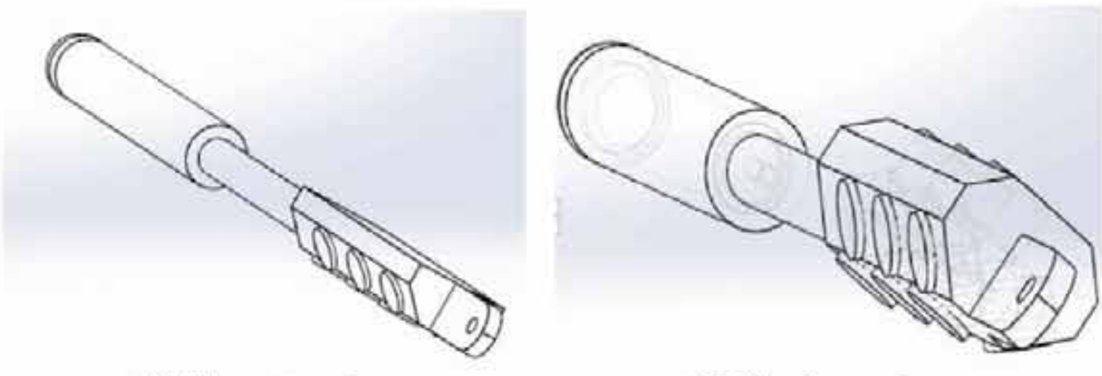
1- Base, 2-Elastic cord, 3-Oscillating pin, 4-Slide bar, 5-flexible connector
(a) Section view of the magnetic drive pin

(b) Base design blueprint

Fig. 4. Internal structure design drawings

auxiliary grasping objects. In addition, the elasticity of the elastic cord can also play the role of holding the grasping force.

The magnetic drive pin of the device is divided into two laps of internal lap and external lap, and the magnetic drive pin at both laps are of polyhedron structure and separate design, so as to ensure the electromagnet between the bars are two facing two in the initial state of the device, so that when objects are clamped, it can achieve the maximum grasping force. In order to obtain greater electromagnetic attraction force, three columns of electromagnets are arranged for each magnetic drive pin, the specific layout form is as shown in Fig. 5a and b.



(a) The outer pin (b) The inner pin

Fig. 5. The pin of hedgehog-inspired pin-array robot hand

2.3 Control Part

The control system adopts the Arduino controller. For the control of the electromagnet, the volume of the output voltage is adjusted through the Arduino PWM output pin to achieve the purpose of the current regulation, so as to realize the control of the gravity of the electromagnet or change the direction of current to achieve rapid dispersion of magnetic drive pins.

When the grasping force provided by the electromagnet is insufficient to pick up the object, the motor assistance is launched to realize the control of the elastic pin to the magnetic drive pin by controlling its circle number. Among them, the current adjustment is controlled by a potentiometer, and the grasping force can be adjusted at any time. The circuit connection and working flow diagram of the device are as shown in Fig. 6.

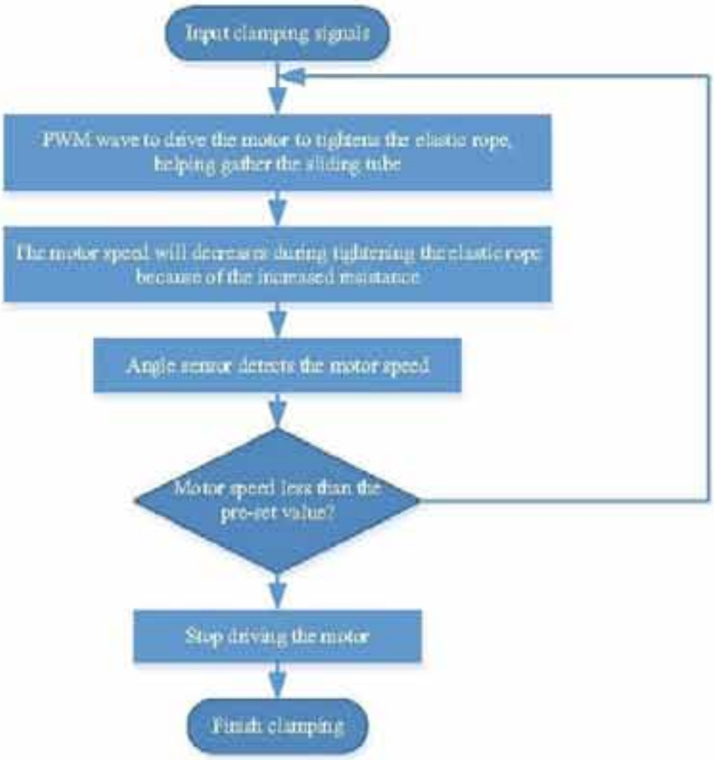


Fig. 6. Logical flow diagram for grasping

2.4 Working Principle

When an object is grasped, with the electromagnet force, the robot arm vertically gets close to the object and compresses it. If the rubber head touches the object or supporting surface in the vertical direction, the sliding tube slides upward relative to the oscillating pin under the compression of the object. Due to the reactive force of the object, the sliding tube produces varying degrees of sliding, then it wraps the objects. For objects of different shapes and sizes, the device has good adaptability, as shown in Fig. 7.

When the device touches an object, the electromagnet is energized, and the magnetic drive pin gathers to the center under the action of radial suction, so that the sliding tube can stick to the object and move the mechanical arm, so as to realize the grasping of the object.

Fig. 7. Grasping various objects

If the radial suction force is insufficient for the magnetic drive pin in the process of grasping objects, the motor will start and drive the spring rope to tighten. The tightening force of the spring string is coupled with the electromagnet suction force to make the sliding tube clamp the objects and have the grasping process go on consecutively.

When an object is released, the device places objects to the bearing surface vertically under the drive of the robot arm, then the electromagnet is cut off from power. At the same time, the motor stops working. The suction force of the electromagnet and the tightening force of the spring rope disappear, thus the sliding tube is in the free state and the object is released.

3 Theoretical Analysis

3.1 Model Design Analysis

The main driving force of the device comes from the electromagnet. The calculation is complicated because there are many influencing factors for the acting force between two electric solenoids. Now, for the convenience of calculation and force analysis, the electromagnet of the device is assumed to be of enfilade deployment. Meanwhile, each electric solenoid generates a magnetic field and produces an influence on other solenoids when calculating the force analysis, so the superposition effect of the magnetic field is neglected for the convenience of calculation. That is, the force analysis of two electromagnets is to calculate the force analysis of two electric cylindrical solenoids.

By referring to literature, Newton's third law is applicable among electricity cylindrical solenoids, and electromagnetic forces only own component in the axis direction. By the electromagnetic field theory, the field energy for the two coaxial electric cylindrical solenoid system is:

$$W = I_1 I_2 M \tag{1}$$

I_1, I_2 are respectively the current of the two electric cylindrical solenoids. M is the mutual inductance of two electric cylindrical solenoids, The force calculation of the upper component along the axis in the external magnetic field of the current-carrying system is based on the principle of virtual work:

$$F = I_1 I_2 \frac{\partial M}{\partial h} \quad (2)$$

The sizes of the magnets of the device are the same, the current of each magnet is the same. By a study of the data, it is found that when the radius of the two coaxial electric cylindrical solenoids is the same, the electromagnetic force F decreases with the increase of the distance. Within a certain range, the electromagnetic force F decreases rapidly with the increase of the distance h. When it is beyond the scope, the decreasing speed of electromagnetic force F slows down with the increase of the distance h; when the distance approaches infinity, the acting force F tends to be zero. The place where h is equal to zero is considered to be a physical singularity because the center of two coaxial solenoids whose radius are the same is impossible to overlap.

3.2 Grasping Force Analysis

Only the gravitational action between adjacent electromagnets is considered here. The external force on the magnetic drive pin is as shown in Fig. 8.

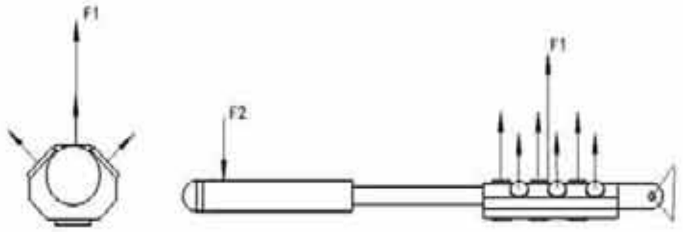


Fig. 8. Force analysis diagram of an oscillating pin.

For the rotation angle of the component of the oscillating pin is small, ignoring the impact of the oscillating angle of the component of the oscillating pin on the force, the force F_1 of the electromagnet on the oscillating pin and the force F_2 of an object on the oscillating pin are both perpendicular to the oscillating pin. In the vertical state, the distance between two adjacent magnetic drive pins in the 3d model is measured and denoted as d. $\frac{F}{\mu I_1 I_2}$ can be obtained. By referring to the data, the magnetic conductivity of the electromagnetic iron core μ was selected, the power voltage U was selected, the voltage was adjusted by potentiometer, and the values of I_1, I_2, and F were obtained. Since the magnetic drive pin is uniformly distributed with 9 electromagnets, it can be obtained that $F_1 = 9F$, where F_1 is the synthetic force of three columns of electromagnets on a single magnetic drive pin. In order to obtain the grasping force F_2, it is set that F_2 works at Point B at the end of the oscillating pipe. Then the entire oscillating pipe assembly is considered as a whole, with the moment balance, it can be obtained that:

$$F_2 \times l_{OB} = F_1 \times l_{OA} \tag{3}$$

In it, l_{OA} and l_{OB} are respectively the point at which the electromagnet acts on the oscillating pin and the distance of the object from the point of action of the oscillating pipe to the hinged point O, thus the size of extrusion pressure of a pin on the device on the object is:

$$F_2 = \frac{F_1 \times l_{OA}}{l_{OB}} \tag{4}$$

In the formula, l_{OA} and l_{OB} are respectively, the arm of the force of F_1 and F_2.

The static friction coefficient μ is also included. Since the inner layer is equipped with 4 magnetic drive pins, the gravity of the weight that can be clamped is:

$$G = 4\mu F_2 \tag{5}$$

F_1 is an electromagnetic force varying with distance. In this device, in order to obtain a large grasping force, measures such as selecting electromagnets with greater magnetic induction intensity, increasing the current passing through electromagnets, increasing the number of electromagnets, increasing l_{OA} and decreasing l_{OB} can be adopted.

In this device, the electromagnetic force generated between adjacent electric solenoids is used to provide the inward contraction force so as to produce grasping force, so the distance between magnetic drive pins and the swinging angle of the magnetic drive pin are the important factors that affect the size of grasping force.

4 Experiment

4.1 Experiment Design

With the three dimensional models, the angle and distance of objects grabbed with different dimensions are simulated, as shown in Fig. 9. The size and shape of the different object are as shown in Table 1. According to the formula for calculating electromagnetic force given above, the maximum weight of the object of this shape and size is obtained theoretically, which provides guidance and reference for practical application.

4.2 Experimental Data Processing

Through grasping simulation of objects of different sizes, we get the maximum grasping force under different conditions through theoretical calculation. In addition, mathematical analysis tools were used to fit the experimental data and the surface diagram shown in Fig. 10 was obtained. In Fig. 10, the horizontal coordinate of the

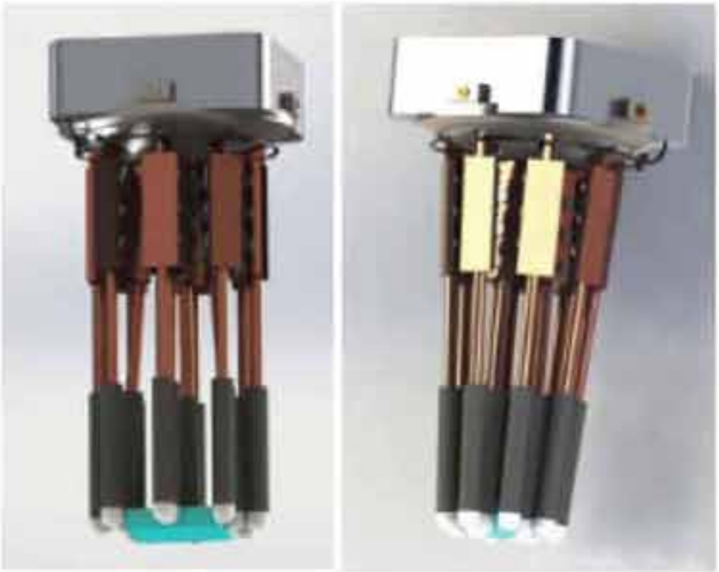


Fig. 9. The experiment of the robot hand grasping objects.

Table 1. Objects of different sizes in the experiment

Width length	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm
10 mm	Ball	Cuboid	Cuboid	Cuboid	Cuboid	Cuboid
20 mm		Ball	Cuboid	Cuboid	Cuboid	Cuboid
30 mm			Ball	Cuboid	Cuboid	Cuboid
40 mm				Ball	Cuboid	Cuboid
50 mm					Ball	Cuboid
60 mm						Ball

surface graph is the horizontal dimension of the clamped object, the vertical coordinate is the longitudinal dimension of the clamped object, and the vertical coordinate is the maximum grasping force of the magnetic drive pin on the object of this size.

The three-dimensional simulation grasping experiment of HIPA Hand is as seen in Fig. 10. By adding the ideal physical model in the three-dimensional model, the shrinkage or opening degree of the magnetic drive pin in the real object grasping process is demonstrated, which is used to provide the swinging angle and relative distance of magnetic drive pin of a specific size. The maximum grasping force can be obtained by applying the corresponding calculation formula.

Through the simulation experiment analysis, we can get the conclusions that the device has the advantages of large grasping force, stable grasping, and strong self-adaptability. But there are still some shortcomings, such as the small grasping force of the overlarge object and the great influence of grasping posture. For improving the deficiency existing at present, we will reduce the distance between magnetic pole displacement in the design of the device in the subsequent versions, and design more laps magnetic pin displacement and more electromagnets. And this will give full play to the advantages of the hedgehog imitation magnetic drive pinball adaptive robot hand device.

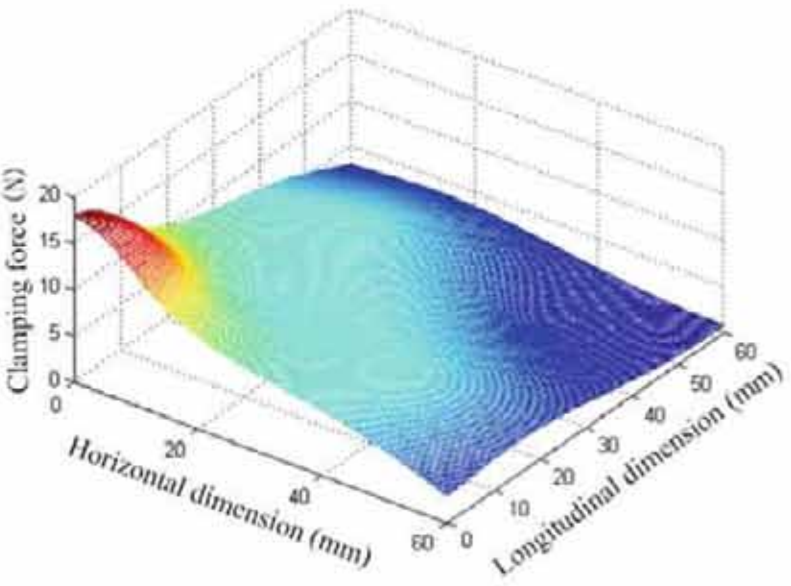


Fig. 10. Relationship between the maximum grasping force and the size of the target object.

5 Conclusion

This paper proposes a novel hedgehog-inspired robot hand (HIPA Hand) with multiple magnetic pins for general self-adaptive grasping. The HIPA hand utilizes electromagnets as the main driving part and the motor as another driving part. HIPA hand can grasp the object of different sizes and shapes. The theoretical analysis and simulation experimental result show that the HIPA hand has the advantage of the quick grasping speed and big grasping force compared with the traditional pin-array grippers.

In future work, we will focus on the development of prototypes and the improvement of experimental performance.

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