

MultiHand: Design and Verification of a Dexterous Hand with Multi-modal Grasping Capabilities

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Abstract—As the end-effector of a robot, the dexterous hand is responsible for grasping and manipulation tasks. With the expansion of application scenarios, a single grasping mode is no longer sufficient to handle different objects and complex environments. In this paper, we design a multi-modal grasping three-fingered dexterous hand, where each finger has a specific function. In addition to performing routine tasks, it is also capable of easily grasping thin and lightweight objects. We propose and validate a dataset of over a hundred objects, covering categories such as food, sports equipment, and household items. The thumb of the dexterous hand in this design is a controllable electromagnet, the index finger is a suction cup finger, and the middle finger is a controllable adhesive finger, with grasping and releasing controlled through heating and cooling. The palm features a jamming design, enabling both grasping and increasing gripping friction. To validate the grasping capabilities of the dexterous hand, we conducted single-finger performance tests and successfully grasped over a hundred common objects, with a grasping success rate exceeding 90%. This dataset was created through 3D scanning, including 102 common objects, and some of the models are open source. The dataset url is: <https://github.com/TNPopy/MultiHand>.

I. INTRODUCTION

With the rapid advancement of robotics intelligence, the functions of robotic end-effectors are becoming increasingly complex, as object grasping and manipulation are now required to be performed by the end-effector [1], [2]. Common types of end-effectors include grippers and dexterous hands. The gripper and hand serve as crucial interfaces for robots to interact with industrial products and the living environment [3]–[5]. In a home environment, robots need to grasp various objects made from different materials and shapes, ranging from smooth plates to rough velvet cloth, from tiny needles to heavy canned jars [6]. In industry, collaborative robotic arms on the production line often need to change end effectors, such as suction cups, magnets, etc., to meet the requirements for grabbing and sorting different products. The diverse grabbing environments make it difficult for traditional single-function grippers to meet the actual production and living needs.

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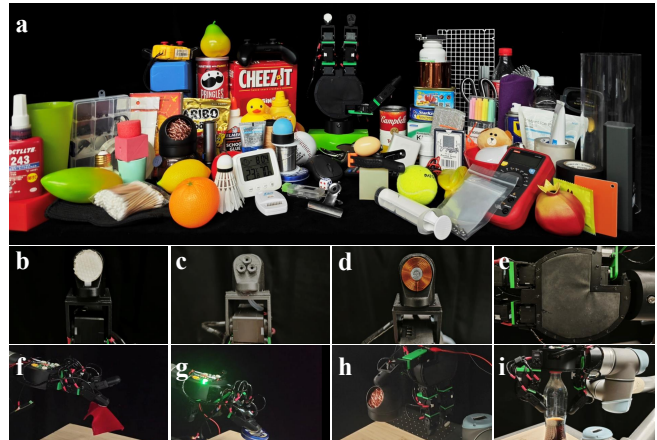


Fig. 1. MultiHand and fingers. (a) MultiHand and the established dataset. (b-c) Controllable adhesive finger, suction cup finger, magnetic finger, and jamming palm. (f-i) Correspond to different gripping methods.

This singular functionality significantly restricts the improvement of production efficiency. With further exploration into end-effectors, techniques such as electromagnetic adsorption, electrostatic adsorption, suction cup adsorption, and controllable adhesive adsorption have gradually been applied for object grasping. In nature, the cooperative action between the terminal suckers and intrinsic muscles of the octopus tentacle provides important insights for the development of novel composite grippers [7], [8]. Traditional suction cups are widely used in industrial applications. New types of suction cups have been proposed in [9], [10], which can achieve normal grasping on non-flat surfaces and exhibit good suction force response. However, they are unable to grasp mesh-like objects, such as fishing nets and filter meshes [11], [12]. As a soft actuator, the suction cup, when mounted on the fingertip, can perform tasks such as pushing and dragging [13]. Traditional industrial grasping end-effectors typically use electromagnets to handle large ferrous objects, such as the transportation of scrap metal. Additionally, high magnetic force often requires larger volumes, and conventional magnets cannot be easily integrated into the interior of a dexterous hand.

Inspired by the above results, we propose an improved dexterous hand with multi-functional grasping capabilities, named MultiHand, as shown in Fig. 1. We propose a grasping dataset for general-purpose scenarios, referred to as the Generic Scene Dataset (GSED).

The main contributions of this work are as follows:

- A multi-functional grasping dexterous hand is designed, featuring controllable adhesive finger, suction cup fin-

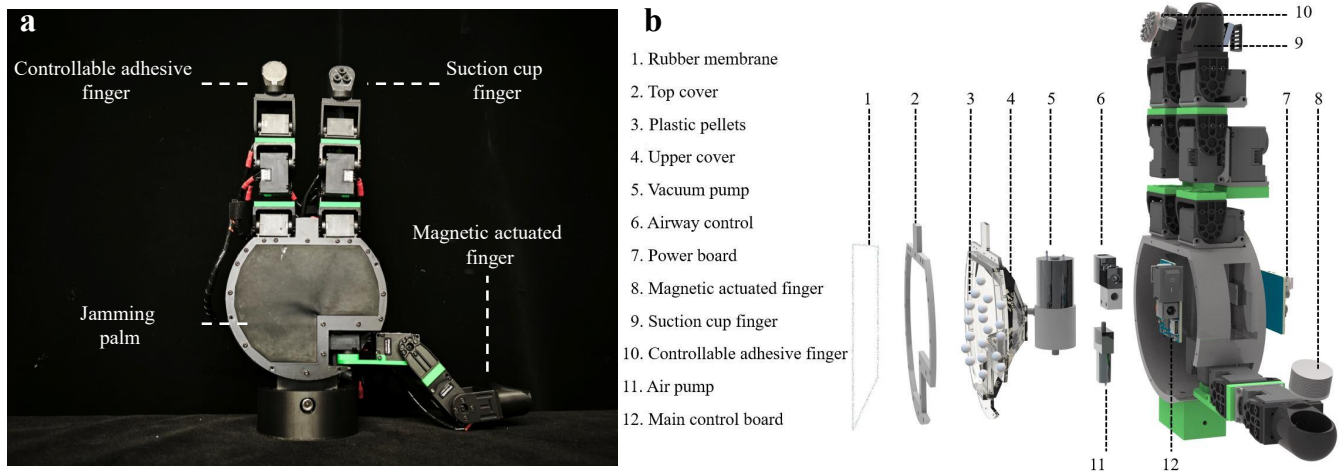


Fig. 2. MultiHand. (a) Physical image of MultiHand. (b) Exploded view analysis of MultiHand.

ger, and controllable magnetic finger. This design enables object grasping for various scenarios and needs, covering over 90% of everyday objects.

- We established the GSED dataset, based on the 40 objects in the CEPB [14] dataset. By creating a custom dataset, we gathered grasping data for 102 objects, covering a wide range of common items such as food, stationery, tools, and sports equipment.
- We designed jamming palm to enhance the operability within the palm and increase the friction during object grasping. Additionally, we embedded the control module and power module of our self-designed dexterous hand, further reducing the overall size.

II. RELATED WORKS

Existing object gripping mechanisms are mainly divided into dexterous hands and grippers. Dexterous hands represent anthropomorphic gripping, while grippers are typically two-finger parallel mechanisms that pinch to grasp objects. The main execution mechanisms under these two types of structures include wrapping [15], adsorption [16], pinching [17], curling [18], and others. These execution mechanisms need to be adjusted according to the gripping scenario and are not universally adaptable. For example, when gripping thin plastic sheets, traditional gripping methods have significant limitations, often requiring the use of suction cups [19]–[21] for grabbing.

In response to thin objects, a clamping mechanism and method were proposed in [22]–[24], similar to the way human fingers perform clamping. However, this mechanical structure requires a high gripping angle, making it difficult to perform flexible gripping operations on the robot body. In [25], an electronic skin with controllable adhesion was proposed. Through different forms of transformation and based on a certain cooling time, it enables the grasping and release of objects. However, the high transformation temperature makes it difficult to perform universal gripping. Soft jamming end-effectors were proposed in [26], [27] requiring large-volume designs for gripping. Single-mode

end-effectors are no longer sufficient for everyday gripping tasks.

III. DESIGN

The entire design of the dexterous hand is divided into two main parts, as shown in Fig. 2. A soft palm and three fingers with different functions: a magnetic actuated thumb, a suction cup index finger, and a controllable adhesive middle finger. The entire dexterous hand has 11 degrees of freedom (DOF) and is directly driven by Robotis Dynamixel XL330 actuators. The main control section is independently designed. An isolated power drive section is designed, with the main power supply divided into the motor drive and main control power supply sections.

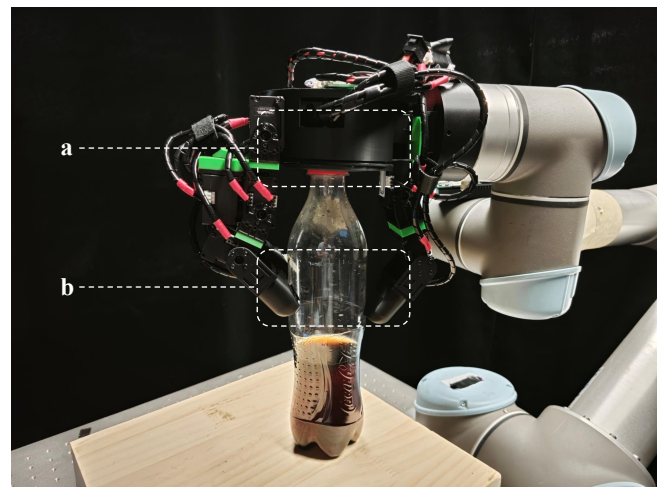


Fig. 3. Opening a bottle with the palm. (a) The bottle cap is embedded into the jamming gripper palm. (b) The fingers rotate the bottle body to open it.

A. Palm design

The palm section primarily includes the jamming gripper soft membrane [28]–[30], the actuator control section, vacuum pump, airpath controller, and inflation components. We designed a jamming palm, which forms a sealed chamber

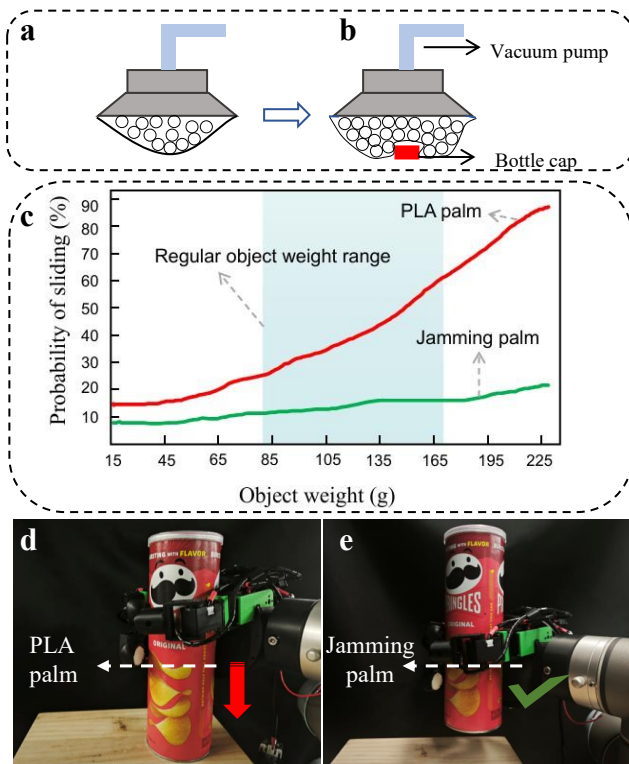


Fig. 4. Jamming palm. (a-b) Jamming gripper principle. (c) Comparison of the weight and drop probability of objects grasped by PLA palm and jamming palm. (d) PLA palm, cylindrical object detachment. (e) Jamming palm, increased friction, securely grasped.

by encasing plastic particles in rubber. A soft gripper is embedded within the palm. On one hand, it allows applying vacuum to the palm. This enables direct object grasping via the palm. When combined with the fingers, it can perform tasks such as opening a bottle with one hand in Fig. 3. On the other hand, in certain special scenarios, such as grasping larger objects like foam bricks or circular acrylic barrels, the soft palm can increase friction. The internal inflatable pump allows the soft membrane to inflate, working in conjunction with the fingers to securely lock the grasped object in Fig. 4.

B. Magnetic actuated finger design

Needles and iron sheets, which are usually difficult to grasp with conventional dexterous hands and grippers. We designed an electromagnet that can grasp and release metallic objects by adjusting parameters such as the number of coil turns and the wire specifications.

By winding an appropriate number of copper coils around the core, we generate the fundamental force for the electromagnet's grasping capability. In the actual design, we primarily focus on the dimensions of the magnet and the strength of the magnetic field. The designed electromagnet uses 0.35mm oxygen-free copper enameled wire, with approximately 500 turns wound around a core with a diameter of 8mm and a height of 12mm. The core material is DT4C, with a carbon content of less than 0.05%.

We need to calculate the inductance after the winding is completed:

$$L = \frac{\mu_0 * \mu_r * N^2 * S}{l} \quad (1)$$

Where μ_0 and μ_r represent the permeability of free space and the relative permeability of DT4C, respectively. N is the number of turns, S is the cross-sectional area of the core, and l is the length of the core. We then calculate the relationship between the magnetic field strength H and the current I , with L_{coil} being the inductance per unit length:

$$H = \frac{I}{l_{coil}} \quad (2)$$

Magnetic flux density:

$$B = \mu_0 * \mu_r * H \quad (3)$$

The magnetic attractive force F is given by:

$$F = \frac{B^2 * S}{2\mu_0} \quad (4)$$

We have calculated the approximate curve of the magnetic attractive force and current as shown in Fig. 5. In practical grasping operations, the grasping force can be adjusted by varying the input current to the electromagnet.

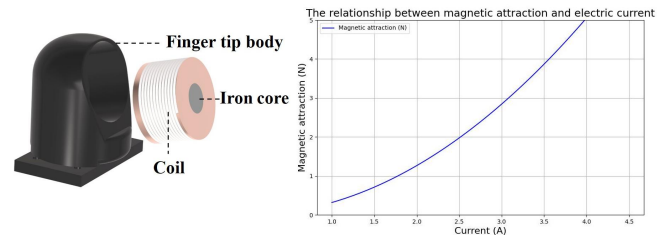


Fig. 5. Magnetic actuated finger and analysis of current and magnetic attractive force.

C. Suction cup finger design

Conventional suction cup grasping typically uses an array layout, where multiple suction cups are arranged on a plane, with each suction cup corresponding to a vacuum channel to enhance the overall suction force [31]. However, this setup requires a large number of vacuum tubes, and when using a single air pump in the design, it becomes difficult to distribute the channels through a rotary connector. If a single large suction cup is installed at the fingertip, it becomes difficult to control the contact angle during the actual grasping process, preventing the rapid formation of a sealed chamber.

To ensure that the fingertip suction cups provide sufficient suction force while maintaining a compact overall size, we

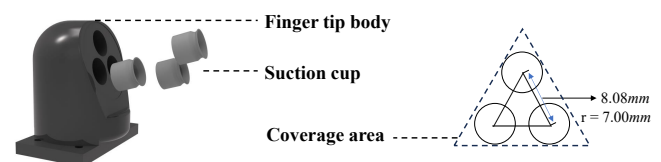


Fig. 6. Suction cup finger and distribution of suction cup positions.

have adopted multiple miniature suction cups arranged in a triangular pattern in this design, as shown in Fig. 6. To ensure the ability to grasp objects with curvature, the spacing between the three suction cups is set to 8.08 mm, with each suction cup having a diameter of 7.00 mm. The total area covered by the three suction cups is 1.154 cm², forming a force-bearing and stable triangular matrix that enables smooth and stable grasping of smooth or curved objects.

Considering the size of the vacuum pump, we have placed the vacuum pump and the air duct adjustment section within the palm, connected by miniature vacuum tubes. Since three suction cups are used in this design, when they come into contact with an object, all three suction cups touch simultaneously, forming a stable contact area and further gripping the object.

In this design, the specifications of the vacuum pump used are 3.5 L/min with a maximum vacuum of -62 Kpa. The diameter of the suction cups is 7 mm. The holding force W (N) of the vacuum suction cup is directly proportional to the pressure P (Kpa) inside the vacuum chamber and the area S (cm²) of a single suction cup. Since the suction cup area is relatively small, we unify the units in the formula for consistency.

$$W = \frac{3 * S * P}{10} \quad (5)$$

The holding force of the fingertip suction cups calculated from the above is 7.15 N, which theoretically allows for the grasping of objects weighing up to 0.75 kg. This is sufficient to handle objects commonly encountered in daily life.

D. Controllable adhesive finger design

Human fingers only have mechanical grasping structures, lacking special functions like the controllable adhesion found in gecko limbs. When handling thin, perforated objects like fabric or paper clips, humans typically use their fingers to carefully pinch them. For robots, this pinching process is even slower, and most end-effectors cannot accomplish this task. This difficulty in grasping has sparked research into robotic adhesive skin.

Conventional adhesive skins are typically difficult to adjust in terms of adhesion, and their overall fabrication is complex and costly. Additionally, in high-frequency daily operations of robots, they tend to experience high levels of fatigue and wear. In [32], the use of the rubber-to-glass transition (R2G) in shape memory polymers (SMP) was employed to achieve controllable adhesion. This phase transition enables the material to function as a soft gripper. However, the transition between the rubber and glassy states is relatively

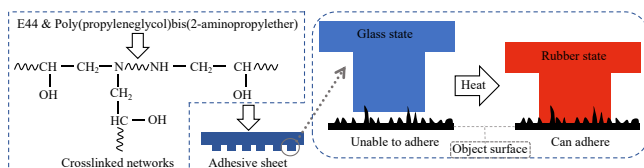


Fig. 7. Reaction process and capture process.

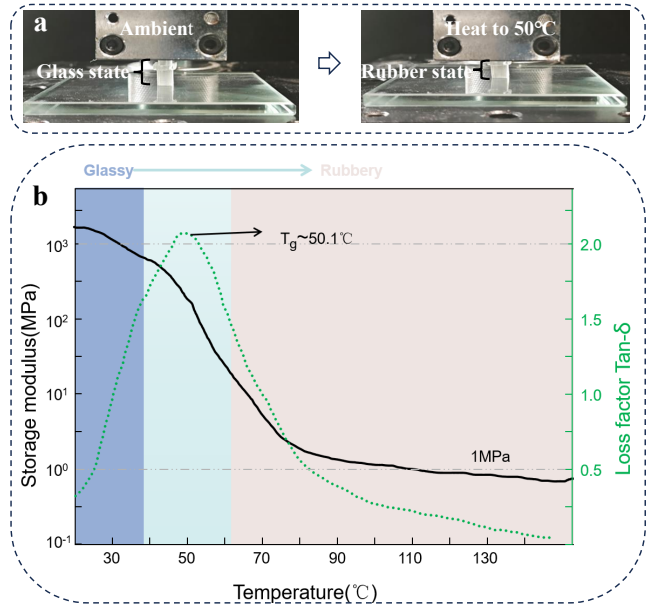


Fig. 8. E44-SMP test. (a) Stress test. (b) Modulus analysis and phase transition process of E44-SMP.

slow, and in practical applications, a certain amount of downward pressure is required to ensure full contact. The long cooling and waiting time is detrimental to the robot's grasping operations.

In Fig. 7, the E44 monomer undergoes a curing reaction with Poly(propyleneglycol)bis(2-aminopropylether) to form a crosslinked networks, enabling adhesive properties. When the controllable adhesive finger is in its glassy state at room temperature, it cannot perform adhesive grasping. However, when the adhesive film is heated to around 49°C, the controllable adhesive finger presses on the object, achieving adhesion. Once cooled, it transitions into a fixed grasping mode, allowing the object to be securely grasped.

The E44-SMP monomer obtained from the reaction was subjected to property characterization, as shown in Fig. 8 (a). We further performed Dynamic Mechanical Analysis (DMA) on the monomer in Fig. 8 (b). By applying qualitative compressive and tensile forces, the deformation shift with temperature was measured. The Ogden model was then

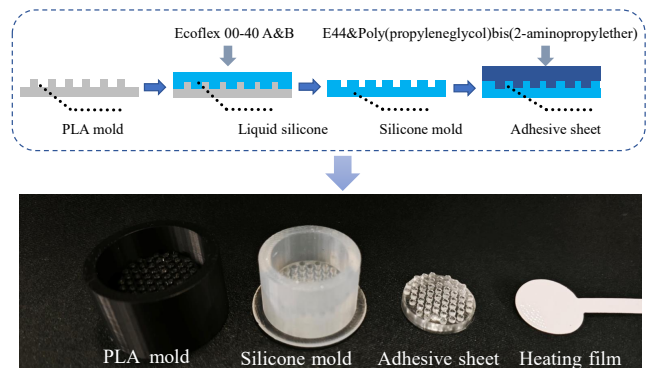


Fig. 9. Molds and preparation process. The hard molds are made from PLA, while the soft molds are made from silicone.

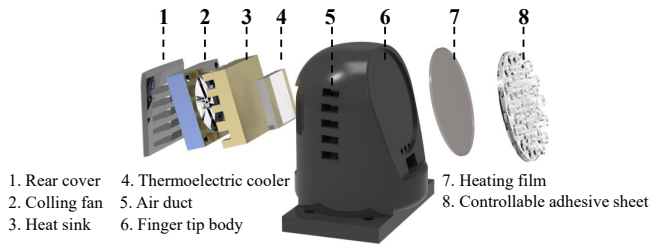


Fig. 10. Structure diagram of the adhesive finger.

employed to fit the strain–stress curves of E44-SMP under different states. The loss factor curve indicates that the actual transition temperature of E44-SMP is around 50 °C. Below 29 °C, the material remains in the glassy state, while above 50 °C, the storage modulus decreases and the material exhibits adhesion in the rubbery state.

In the design of the controllable adhesive finger, we adhere to the principles of low cost, reliability, and efficient adhesion and detachment. We created the adhesive finger mold using silicone rubber. By mixing Macklin’s epoxy resin E44 and Poly(propyleneglycol)bis(2-aminopropylether) at proper proportion, stirring the mixture, and pouring it into the silicone mold, we initiated a curing reaction by setting the temperature to obtain the adhesive finger monomer in Fig. 9. Subsequently, we covered it with a self-designed heating film to achieve the controllable adhesive state.

In our design, to reduce the cooling time after the adhesive finger contacts the object and improve overall grasping efficiency, we embedded a thermoelectric cooler at the fingertip in Fig. 10. Additionally, a heatsink and a micro-sized cooling fan were placed within the confined space. All components are within the 15 mm × 15 mm size range, ensuring a lightweight fingertip design.

IV. EXPERIMENTS AND RESULTS

A. Single-finger performance testing

The motor used in our design is the Robotis Dynamixel XL330, which has a stall torque of 0.6 N·m and a rated torque of one-fifth of the stall torque, sufficient to meet the grasping

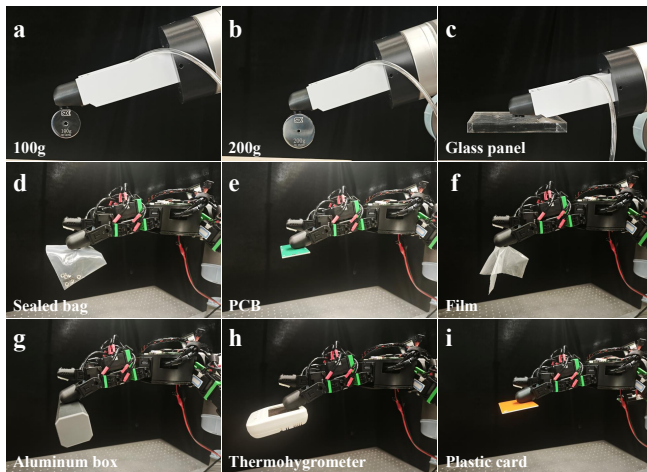


Fig. 11. Suction cup single finger. Grasping performance test and single finger grasping, covering PCB, cards, thermometers, and sealed bag.

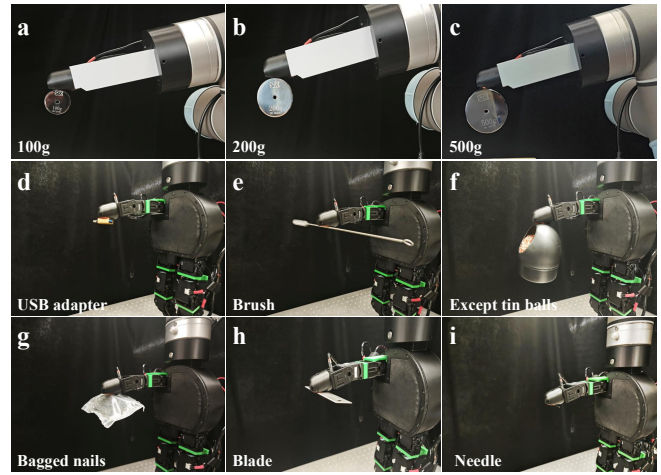


Fig. 12. Magnetic single finger. Grasping performance test and single finger grasping, covering needles, nails, and metal objects.

requirements of everyday tasks. We conducted attachment capability tests on individual functional fingertips to verify the grasping ability of the MultiHand.

Since most common objects weigh less than 500g, we primarily conducted tests on grasping 100g, 200g, and 500g weights in our experiments. Fig. 11 (a-c) shows our tests on the suction cup finger, grasping 100g, 200g weights, and a glass plate. Fig. 11 (d-i) presents the suction cup grasping experiments, verifying that MultiHand can easily grasp flat, smooth objects such as PCBs and cards.

Fig. 12 (a-c) shows the tests for the magnetic actuated finger grasping. Since the magnetic attraction force of the magnet is related to the input current, we can increase the grasping capability up to 500g by adjusting the current, which is sufficient for daily grasping operations. Fig. 12 (d-i) shows the tests for the magnetic actuated finger grasping. MultiHand is able to easily pick up small metal objects such as needles, nails, USB adapters, and other similar items.

Fig. 13 (a-b) shows the performance tests for the controllable adhesive finger. The tests primarily evaluate its grasping capability with 100g and 200g weights. Fig. 13 (c-i) shows

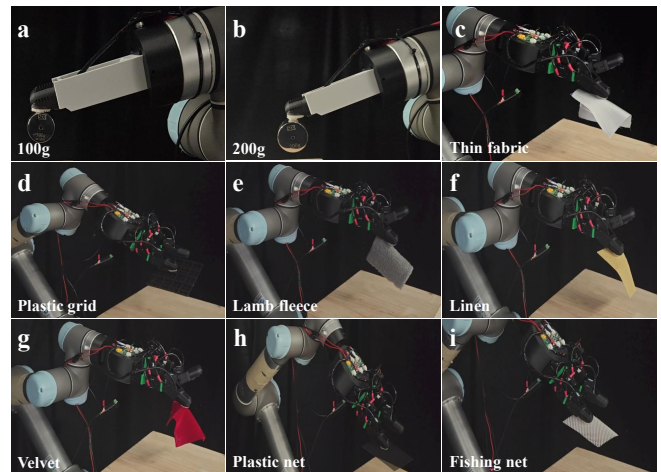


Fig. 13. Adhesive single finger. Grasping performance test and single finger grasping, covering velvet, plastic mesh, and linen.

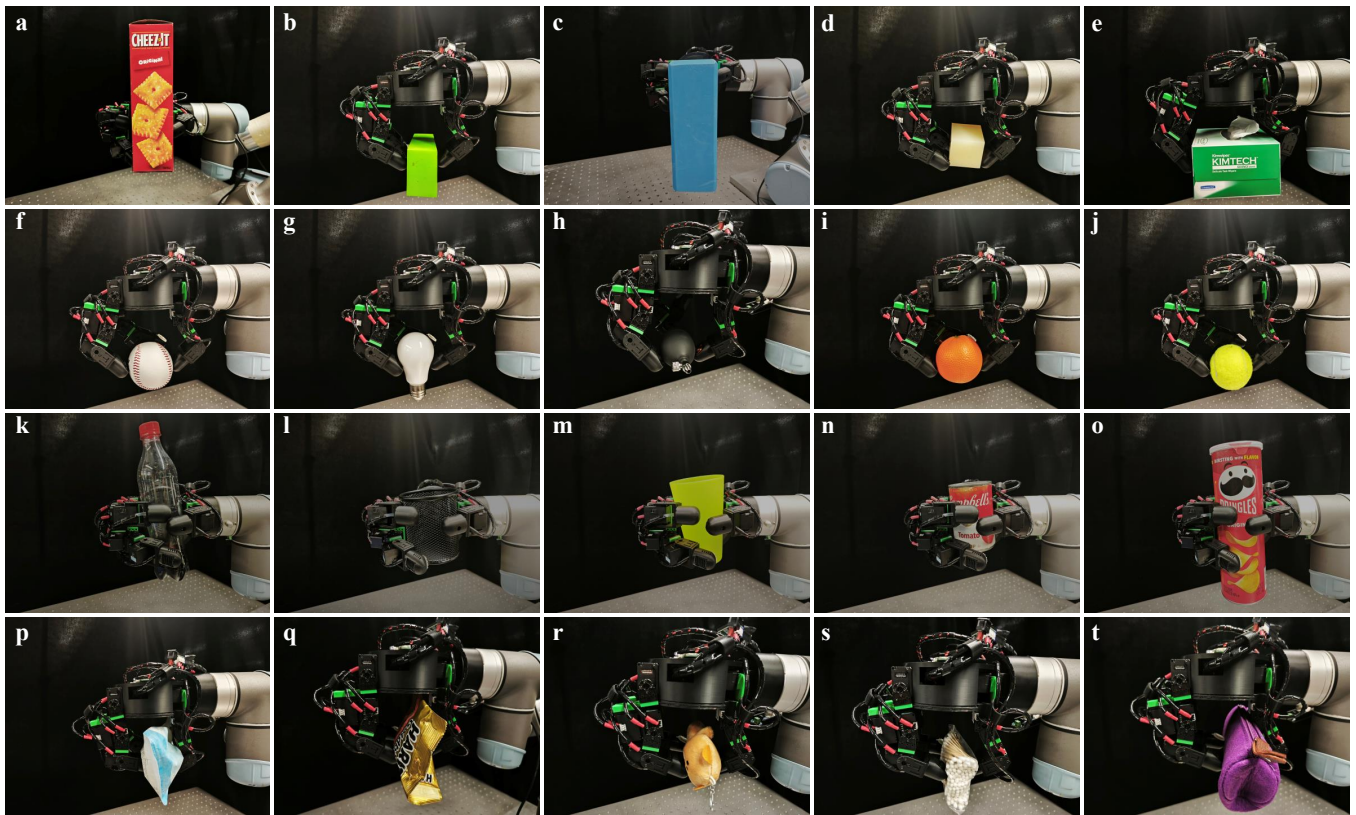


Fig. 14. MultiHand grasping operations. (a-e) Represent the set of rectangular objects. (f-j) Represent the set of spherical objects. (k-o) Represent the set of cylindrical objects. (p-t) Represent the set of soft objects.

TABLE I
GRASPING SUCCESS RATE OF MULTIHAND ON THE GSED DATASET

Name	Shape	Type	Number of Objects	Item	Grasping Success Rate
Category 1	Rectangular object	Household items, food	24	Cheez-It cracker box and others	96%
Category 2	Sphere	Sports equipment, food	18	Tennis balls, table tennis balls, oranges, and others	89%
Category 3	Cylinder	Food and household items	20	Cola bottles, chip cans, cups, and others	92%
Category 4	Software	Stationery, household items	19	Cotton swabs, stuffed toys, and others	88%
Category 5	Small size	Industrial products, household items	21	USB adapters, Downloaders and others	90%
Total			102		91%

the grasping tests for the controllable adhesive finger. We tested the grasping ability on materials such as fishing nets, linen, velvet, and plastic mesh. After multiple rounds of testing, the success rate of the adhesive finger was 95%.

B. GSED dataset and grasping-related experiments

In this design, to validate the grasping ability of Multi-Hand, we created the GSED dataset, which includes over a hundred common objects from daily life. In Fig. 14 (a-e) represent the set of rectangular objects, (f-j) represent the

set of spherical objects, (k-o) represent the set of cylindrical objects, and (p-t) represent the set of soft objects. The dataset covers sports equipment, food, industrial products, household items, stationery, and more.

Table I presents our classification of the dataset and the corresponding grasping success rate statistics. We have divided all items in the dataset into five categories: Rectangular objects, including biscuit boxes, foam bricks, storage boxes, etc; Spherical objects, including ping-pong balls, tennis balls, baseballs, light bulbs, etc; Cylindrical objects, including

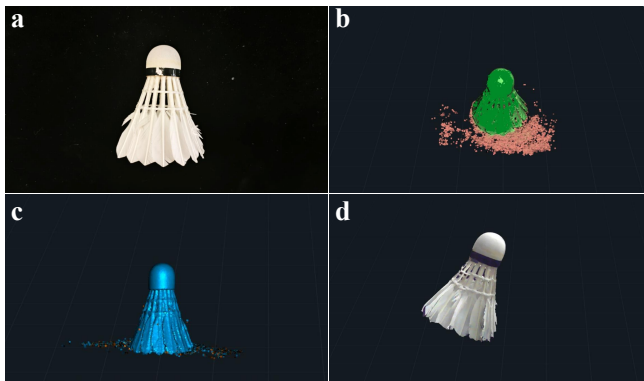


Fig. 15. 3D scanning and creation of open-source models for the GSED dataset. (a) Physical object. (b) Scanning process. (c) Unrendered output file. (d) Complete output file.

water bottles, pen holders, acrylic barrels, etc; Soft objects, including cotton swabs, tissue rolls, candies; Small volume objects, including dice, keys, flash drives, etc. All classified items are commonly encountered in daily production and life. The grasping success rate represents the average success rate after five attempts to grasp each object in a category. The grasping capability of MultiHand covers over 90% of objects encountered in daily life.

To ensure the generality of our data, we performed 3D scanning on each object in the GSED dataset in Fig. 15, created independent models, and open-source some models. Provide assistance for subsequent research within the field and reduce research cost investment.

C. Operational performance verifications

MultiHand not only has the ability to perform specialized grasping tasks but also retains the dexterous operation capabilities of conventional dexterous hands, as shown in Fig. 16. In addition to excelling in highly complex grasping tasks, MultiHand is also capable of performing common everyday operations, such as drilling with an electric drill, scanning items with a barcode scanner, pulling tissues from a tissue box, and opening drawers. These capabilities are made possible by our optimized design of the hand size and palm structure, allowing the dexterous hand to perform fluid operations in various environments.

MultiHand is a three-finger structure, consisting of the thumb, index finger, and middle finger, with a total of 11 degrees of freedom. We found that everyday routine tasks can be performed with just these three fingers, so we optimized its design to cover typical operational environments. Compared to traditional robotic hands, MultiHand is capable of adapting to a wide variety of complex object grasping tasks. Whether it is handling precision components in industrial settings or performing everyday tasks in a domestic environment, MultiHand can ensure smooth task completion with its efficient control system. This flexibility and multi-modal functionality provide it with vast potential applications across various fields, from industrial automation to smart homes.

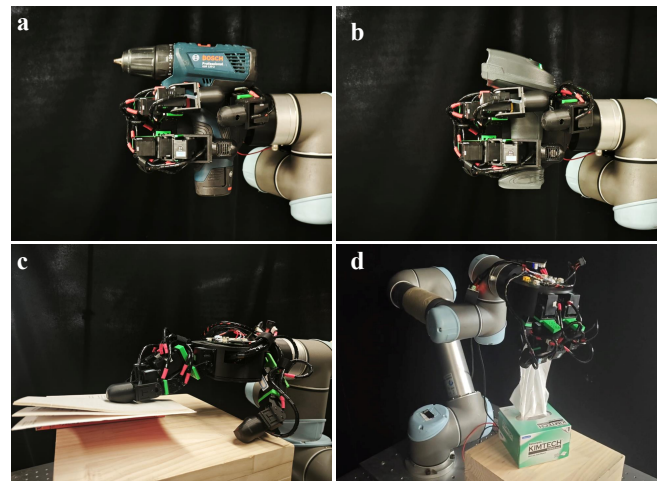


Fig. 16. MultiHand operation performance test. (a) Operating an electric hand drill. (b) Operating a barcode scanner. (c) Turn over a piece of paper. (d) Pulling out a tissue.

V. CONCLUSIONS & FUTURE WORK

This paper designs a multimodal grasping dexterous hand called MultiHand. Each finger of the MultiHand possesses special functions beyond those of a conventional dexterous hand, and the palm has been redesigned to assist the fingers in completing grasping tasks. The thumb is a magnetic actuated finger, capable of easily grasping small objects in daily life, such as needles, paperclips, and similar items. The index finger is a suction cup finger, capable of gripping smooth and flat objects such as glass, paper, and similar items. The middle finger is a controllable adhesive finger, capable of adhering to fabrics, fishing nets, and other mesh-like objects, allowing for trace-free grasping. The palm is designed as a jamming gripper palm, made of a soft material that assists the fingers by increasing friction to complete the grasping action. Additionally, the palm can perform grasping tasks independently. We also propose a multi-dataset GSED for grasping samples, establishing a collection of over a hundred grasping samples for the first time. This dataset covers items such as food, stationery, sports equipment, industrial tools, household items, and more, providing data services for the multimodal hand field.

In future work, we aim to refine the data samples and provide a more standardized dataset. We plan to use reinforcement learning to train the designed hand, enabling autonomous grasping in multiple scenarios. Additionally, we will improve the coordination between the fingers and the palm, while reducing the overall size of the hand.

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