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Precision Grasping and Manipulation of Small Objects from Flat Surfaces using Underactuated Fingers

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***Abstract*—In this paper we demonstrate an underactuated finger design and grasping method for precision grasping and manipulation of relatively small objects. Taking a cue from human manipulation, we introduce the flip-and-pinch task, in which the hand picks up thin objects from a table surface by flipping it into a stable configuration. Despite the fact that finger motions are not fully constrained by the hand actuators, we demonstrate that the hand and fingers can be configured with the table surface to produce a set of constraints that result in a repeatable quasi-static motion trajectory. This approach is shown to be robust for a variety of object sizes, even when utilizing identical open-loop kinematic playback. Experimental results suggest that the advantages of underactuated, adaptive robot hands can be carried over to dexterous, precision tasks as well.**

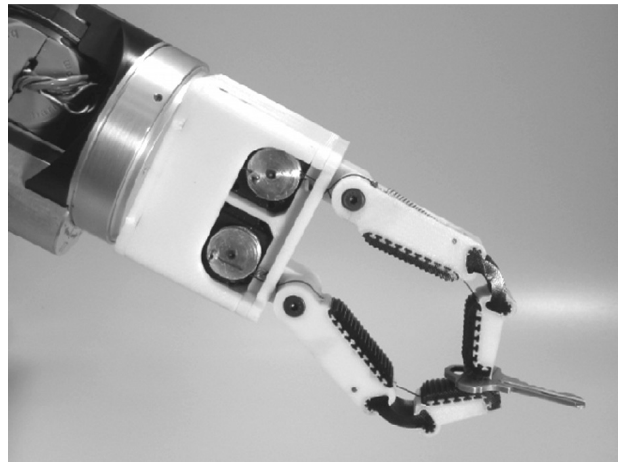

Fig. 1. A thin object, such as a key, must often be reoriented during the grasp acquisition process. Consequently, in-hand manipulation is critical to the operation of any dexterous robot hand.

I. Introduction

GRASPING medium- and large-sized objects in power grasps using underactuated hands is a well-studied problem. Hands such as Hirose's soft gripper [1], Gosselin and Birglen's MARS and SARAH hands [2], and Dollar and Howe's SDM Hand [3] are highly successful at conforming to the shape of an unknown object because the hand actuators do not fully constrain the motion of the fingers, instead using a differential transmission to move the fingers in a coupled fashion, similar to a rocker/bogey transmission [4-5]. This enables the fingers to adapt to a wide range of shapes while exerting fairly small forces. Once contact is made with a grasped object, the internal constraints between the hand and object create a stiff enveloping grasp, effectively assembling the object to the end of a manipulator.

The same design features that enable robust, adaptive power grasping also make precision grasping and in-hand manipulation more difficult. Underactuated hands rely on contact with a grasped object to fully constrain the kinematics of a grasp. A small object, such as the key shown in Fig. 1, will not provide enough contact constraints on the hand to fully define its instantaneous motion. Instead, the elasticity of the fingers will play a role in determining the equilibrium position of the hand [6-7]. Limiting the number of actuators in a hand also has the natural effect of reducing the ability to maintain force closure on a grasped object (due to unconstrained degrees of freedom in an underactuated hand) while independently specifying a kinematic trajectory, as described by Salisbury [8]. Nonetheless, some in-hand manipulation is possible with an underactuated hand. The authors have previously shown that an underactuated hand is capable of moving objects along the minimum-energy trajectories, provided that the frictional contact constraints can be maintained passively by the underactuated mechanism [9]. By respecting the physics of a particular manipulation task, surprisingly dexterous behaviors can emerge from an underactuated hand.

This paper presents experimental results from one dexterous task performed with an underactuated hand: acquiring a pinch grasp on a thin object initially placed on a table or other flat surface – the typical scenario for grasping small objects and one that very few robot or prosthetic hands can manage. Both manipulation and grasping are involved, since the object must be reoriented from its initial configuration in order to pinch it from both sides, as illustrated in Fig. 1. A human-inspired flip-and-pinch motion was used as the basis for the motion of the robotic hand. Unlike typical approaches to dexterous fingertip manipulation, the underactuated manipulation task shown here does not rely on detailed computation, sensing or control in order to be robust, unlike much of the previous work in the area [10-12].

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The basic framework outlined in the authors' previous work on underactuated manipulation was used to analyze and optimize the task strategy [9]. Careful consideration of the constraints on the hand, both from internal contacts and environmental affordances, was used to find the kinematic trajectory and the reaction forces on the object. Knowledge of these reaction forces was used to design fingertips that improved the ability to maintain frictional contact with the grasped object throughout the task. The grasping primitive was capable of successfully picking up objects having a significant range of thicknesses and diameters, as evidenced by trials over a variety of coins.

This paper is organized into several sections. First, the design of the underactuated fingers used in this paper will be introduced, and the basic task will be outlined. Second, the flip-and-pinch motion will be analyzed, and the nature of the frictional constraints on the fingertips will be discussed. Finally, results from a series of trials will be shown, demonstrating the current ability of the hand to pick up thin objects and other common small, difficult-to-grasp from a flat surface.

II. Task Description

A. Hand Description

The two-link fingers used for this work were developed in collaboration with iRobot Corporation (Bedford, MA, USA), and are part of a larger project to develop a low-cost robot hand. Figure 2 depicts the finger geometry. The proximal finger joint is a pin joint, having a parallel antagonistic spring. The distal joint is a flexure hinge, whose geometry was chosen to obtain a 5:1 angular stiffness ratio with the proximal joint, as previous studies recommend [3]. A single tendon is attached to the distal link, so that the motion of the two links is differentially coupled together, in a fashion similar to the links of Hirose's soft gripper [1].

The basic design of these fingers was driven by the need for a general purpose hand. The precursor hand, the SDM Hand, was effective for power grasping, and the necessary elements of this design, such as the joint stiffness ratio and the torsional compliance of the distal joint, were copied. Changes, such as the use of a pin at the proximal joint and the shortening of the distal link, were chosen to improve the ability of the hand to exert larger fingertip forces for pinch grasping. The only finger design parameters altered while considering the task shown in this paper related to the ridges on the fingertip pads; the effect of these changes will be discussed later.

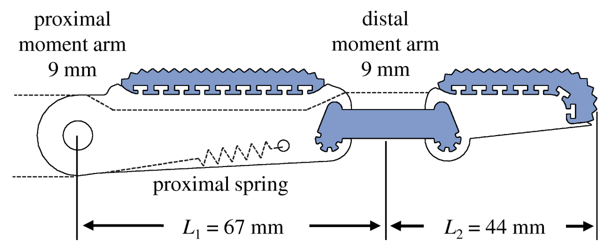

Fig. 2. The two-link fingers used for this experiment had a proximal pin joint and a distal flexure joint. The distal moment arm (distance from the tendon to the flexure centerline) was designed to match the 9 mm radius on the proximal joint pulley. The proximal spring was designed to produce a 1:5 proximal to distal joint stiffness ratio.

To build the planar hand used for this study, two of these fingers were arranged in an opposed configuration, as shown in Fig. 3, with proximal joints located 52 mm apart. Each motor was independently actuated by a single Robotis Dynamixel RX-28 servo motor. The hand was attached to the end of a Barrett Whole Arm Manipulator (WAM). No contact or force sensors were used to control the hand. Instead, open-loop kinematic playback was used to position the wrist in the Cartesian workspace and control the operation of the two finger servos.

B. The Flip-and-Pinch Task

Figure 3 depicts the process of a human being grasping a coin from a table. The thumb is planted on one side of the

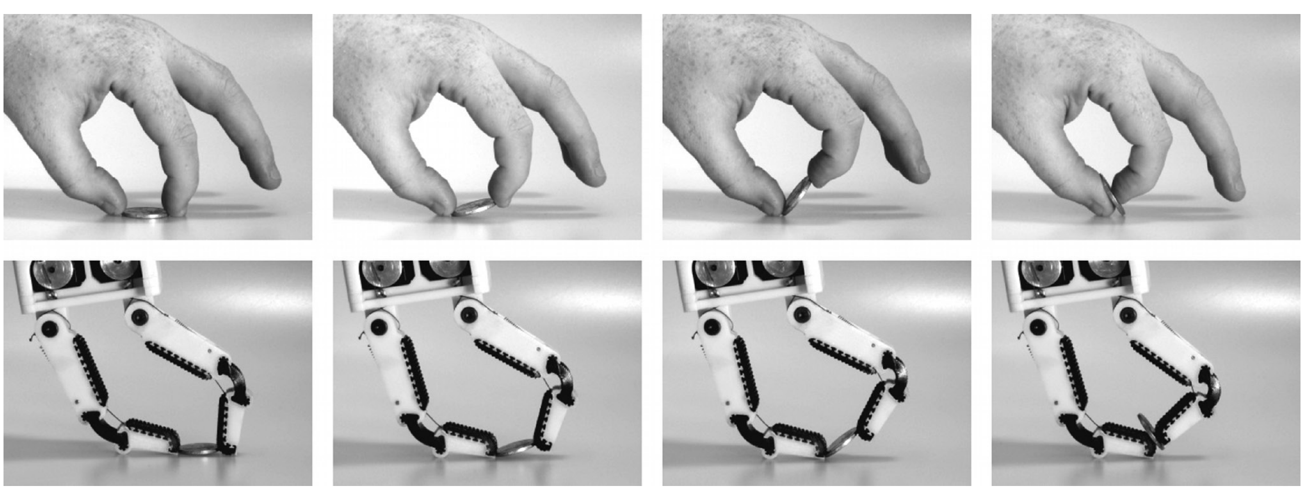

Fig. 3. The task described in this paper, flipping a thin object up to acquire a pinch grasp, was inspired by the human hand. Below, the authors' underactuated hand demonstrates the same procedure using kinematic playback.

coin, pinning the object to the table so that it pivots about the tip of the thumb. An opposed finger is then flexed until it contacts the other edge of the coin, and rotates the coin up into the hand. When the angle between the coin and the table is large enough, the fingertip loses contact, and the coin is flipped into a pinch grasp between the finger and thumb.

The lower row of photographs in Fig. 3 shows how the robotic hand was used in a similar fashion to pick up the same coin. Because the stationary finger (hereafter referred to as the thumb) was underactuated, the whole distal link was rested flat on the surface of the table, providing additional constraint, which ensured that the thumb could not rotate or translate. Apart from this modification, the procedure remained the same. The opposing finger was swept along the surface of the table by pulling on the actuator tendon, and lifted the coin into a vertical configuration. As the coin rotated upwards, contact was lost and the coin flipped into a pinch grasp similar to the human hand. Many experiments, shown in the video accompanying this paper, demonstrated that the same kinematic trajectory for the actuators (planting the thumb, then sweeping the finger into a pinch configuration) was capable of grasping a variety of objects, having different thicknesses and widths, without altering the trajectory of the finger actuators. In this respect the flip-and-pinch process is very similar to the power grasp process for the SDM Hand outlined in [3], in which the hand is placed loosely around an object before pulling inward on a set trajectory.

III. Modeling the Flip-and-Pinch Process

The experimental observation of a repeatable method for acquiring thin objects in a pinch grasp using standard two-link underactuated fingers is encouraging, but it is important to understand the driving design features affecting the success or failure of the manipulation task. Because the joint torques on underactuated hands are not determined entirely by a control policy, the physics of the hand and object as a whole system must be considered. A simplified linkage version of the hand, shown in Fig. 4, was constructed, using the geometric properties taken from Fig. 2. This model utilized constrained energy minimization to predict the equilibrium configuration of the underactuated hand as the fingers close on an object and lift it off the table. Several key insights were uncovered in the process:

1. Although the fingers are underactuated, the constraints imposed on the hand by contact with the object fully define the motion of the fingers while the object is being lifted off the table.
2. Consequently, the object is in quasi-static equilibrium throughout the lift-and-pinch process, and the reaction force direction can be inferred from this.
3. Based on knowledge of the reaction forces, the fingertips of the fingers can be designed to maximize the robustness of the contact constraints during the critical phases of the process.

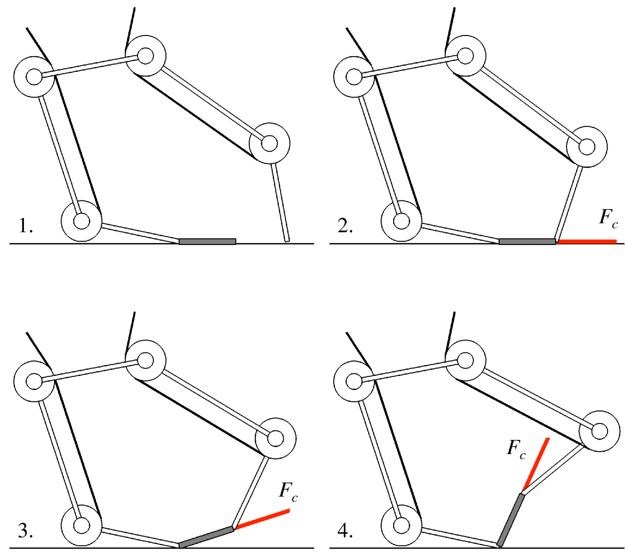

Fig. 4. Simulation of several stages in the flip motion. The direction of the constraint force vector F_c is shown for frames 2, 3, and 4. This force is always aligned with the thin object, because there can be no torque on the object.

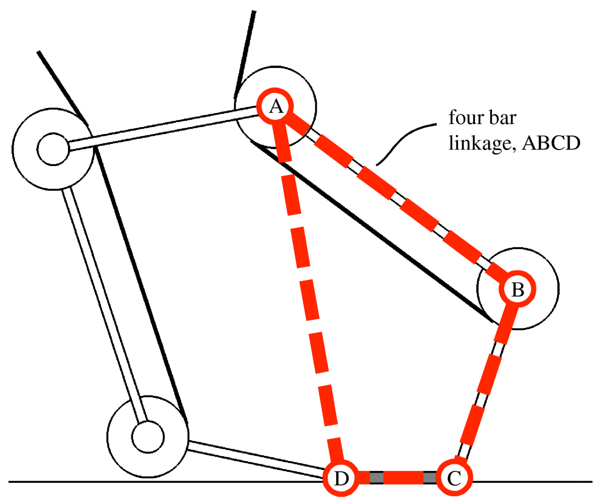

Fig. 5. When the fingers make contact with the thin object, they act as a four bar linkage, ABCD, whose shape is fully defined by the actuator tendon. Points A and D are fully constrained by the wrist position and by contact with the table.

These three observations will be expanded in this section.

A. Fully Constrained Hand Motion

In the linkage model of the hand, no-slip contact constraints of the fingertips with the thin object were treated as pin joints, because the small contact area was unable to support a moment. The distal flexure joint was also modeled as a pin joint for simplicity. Based on these simplifications, the kinematics of the flipping motion are reduced essentially to a four bar linkage, once the two fingers have both made contact with the object. The linkage is illustrated in Fig. 4 as the quadrilateral ABCD. The immovable wrist and table fully constrain the thumb, so points A and D on the linkage are fixed. The motion of the distal joint, B, and the fingertip, C, are exactly constrained by the excursion of the actuator tendon. This partially explains the experimental repeatability of the flip-and-pinch motion – whatever the object width, the mechanism will lift the object once the finger has slid across the table and made contact, as depicted by Fig. 5. It also indicates that an underactuated approach to this task is intrinsically easier in some respects to a fully actuated finger, because no computation is needed to calculate the relative trajectories of the two finger joint angles during the process. The passive constraints do this automatically.

The assumption that the distal flexure joint is a pin joint is not entirely correct. A flexure joint admits multiple parasitic motions, and these motions do add a small phase after contact in the real system, in which both fingers flex slightly in compression rather than immediately rotating the object upward. After this compression has happened, however, the observed motion is quite consistent with the linkage model.

B. Equilibrium Forces

Because the motions of the hand and object linkage are kinematically constrained by the excursion of the actuator tendon on the moving finger, it is safe to assume that the system is in quasi-static equilibrium throughout the process of lifting the object off the table. This was experimentally confirmed by the observation that the trajectory of the fingers did not change as the grasping and reorientation process was sped up or slowed down. The important implication of quasi-static equilibrium is that the net torque on the thin object must always be zero. Because the constraints between the fingertips and the object cannot support any torque, the constraint force F_c on the grasped object must always be aligned with the object, as shown in Fig. 4.

C. Fingertip Geometry and Contact Constraints

The direction of the reaction force is crucial to understanding how the frictional constraints at the tip of the finger operate. The no-slip constraints on the fingertips rely on the constraint force F_c lying within the friction cone of the fingertip contact, as shown in Fig. 6. When the object is lying flat against the table, it is difficult to maintain any frictional contact between a smooth fingertip and the thin object. Most of the observed failures to grasp resulted from failure to satisfy these constraint forces.

Following the human example of fingernails, the addition of sharp features to the fingertip enabling side-on contact with thin objects improved the frictional contact on the grasped object. Rather than relying solely on fingernails, the fingers were modified to include ridges, depicted in Fig. 6, so that the contact normals along the finger surface varied widely. After modification, the fingers made contact on the grasped objects on the side of the ridges. The contact normals on the side of the ridges are far more favorable to maintaining frictional contact immediately after the finger

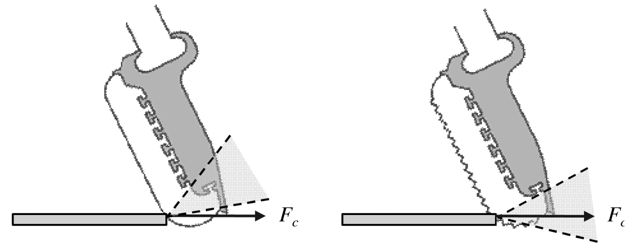

Fig. 6. The finger tip constraints can be maintained by adding ridges to ensure that contact normals, and hence the friction cone, are aligned with the edge of the object.

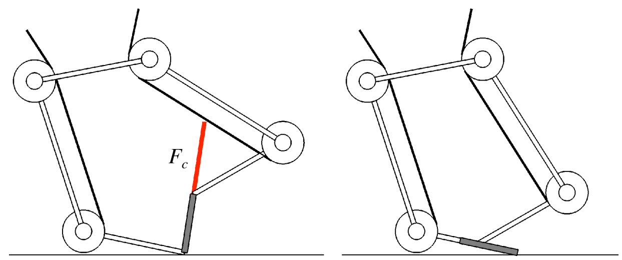

Fig 7. When the contact constraints on the tip are broken, the fingers will snap to the minimum-energy configuration. This simulation shows the equilibrium pinch grasp, at right, corresponding to the constrained configuration shown at left.

contacts the object.

Breaking the contact constraints is also critical to the success of the flip-and-pinch grasp acquisition process. When the object is in a vertical or nearly vertical configuration, the contact constraints are lost as the reaction force vector on the object rotates outside of the friction cone. The exact location of this zero point varies depending on the size of the object. Figure 7 shows a simulated case for a 25 mm wide object, based on observed results. The post-contact configuration of the fingers is also very important to note. Once the constraints with the object are broken, the finger will quickly seek its equilibrium configuration constrained against the other finger, shown at the right hand side of Fig. 7. The new minimum-energy configuration of the fingers is in a pinch grasp configuration, and by tightening on the tendons, a stable pinch can be maintained. Thus, the passive mechanics of the fingers again result in a behavior that appears quite dexterous, while in fact no elaborate modeling, planning or sensing is required.

D. Summary

Based on a simplified linkage analysis of the flip-and-pinch process using two-link, one-actuator fingers, we have shown that the contact constraints with the grasped object and the external contacts with the environment (the table) provide a great deal of structure to the task. Manipulating a thin object by lifting it and rotating it into a vertical orientation between the fingers is achieved by the four-bar linkage structure of the constrained hand/object system. The reaction forces on the object are determined by the nature of the contact constraints and the quasi-static nature of the task, and once the object is rotated between the fingers, they lose contact with the object and settle into a pinch configuration. The mechanical intelligence of the underactuated hand does all of this without requiring sensing or control.

IV. Experimental Validation

In order to quantify the performance of the hand at picking up thin objects, the authors evaluated its success rate for the pinch-and-flip task on a collection of coins. Currency provided a varied a set of test cases with diameter and thickness dimensions that most challenged the hand's capabilities. Many coins have small enough thicknesses that even human hands have difficulty picking them up from flat surfaces. Initial testing showed that the hand could repeatedly pinch and flip objects of diameter and thickness that did not require the use of fingernails. Fig. 9 shows an example set of objects that the hand could pinch and flip with a high degree of repeatability, and Fig. 10 shows the distribution of coins used in this study.

Positioning of the hand during test trials was accomplished through the Barrett Whole Arm Manipulator (WAM). In each trial, the hand starts above the table and coin to be grasped, as shown in Fig. 11. The hand is then lowered vertically such that the thumb appendage is pinned against the table, after which the free finger sweeps in and pinches the object. Coins were positioned by the authors at the approximate target point, with an accuracy of ~0.5 cm. The attempt is then considered successful if the hand can lift the coin without dropping it or having it slip within the final grasp configuration. 10 trials were performed per coin in the test set.

V. Results and Discussion

Fig. 12 shows the results of this study for 37 coins, with diameters between 16-32 mm and thicknesses between 1-3 mm. Despite the use of the same hand trajectory regardless of coin dimensionality and purely open-loop playback, the hand has a success rate of 70% or higher for all coins with thicknesses above 2 mm. The assumed contact constraints for the pinch-and-flip task became more difficult to maintain for thicknesses less than 2 mm.

Specifically, smaller thicknesses increase the chance of slip between the object and the sweeping finger. Although slip is also expected to occur on objects of large thicknesses, the sweeping finger has limited surface area on its tip to successfully engage the object. Fabrication constraints limit the minimum size of the fingertip ridges, and consequently, the finger's effectiveness in aligning the friction cone at contact with the edge of the object.

Also, the authors noticed that as the coin thickness approached the thickness of the fingernail, the hand had greater difficulty pinning the object beneath the thumb appendage. With the contact point between the thumb and coin above the table surface, it became more difficult to

Fig. 9. Objects successfully grasped by the hand using the same flip-and-pinch motion.

Fig. 10. An array of coins, denominated in AUD, EU, CAD, CHF, RMB, and USD were used as test objects to determine the range of width and thickness graspable with the hand.

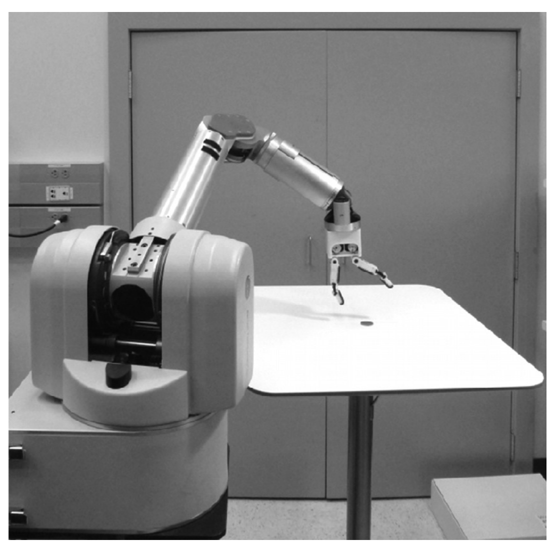

Fig. 11. A Barrett Whole Arm Manipulator was used in conjunction with the authors' hand to test the flip-and-pinch task.

align the contact normals appropriately.

Adjusting the hand position, namely the vertical offset from the surface and the angular offset of the hand with respect to the table surface normal, according to the size of the object would increase the success rate of the pinch-and-flip task. The hand position largely determines the behavior and degree of flexing in the thumb appendage before the hand reaches a stable grasp configuration. However, in the interest of minimizing the hand's dependence on positioning accuracy, it is more advantageous to first consider changes to finger parameters.

VI. CONCLUSION

While underactuated, compliant robotic hands have had a great deal of success in obtaining power grasps, they are to date far less adept at performing dexterous, precision tasks on much smaller objects. Indeed, very few general-purpose robotic hands have had success at grasping small objects from their resting surfaces. This paper introduces modifications to the adaptive SDM Hand for picking up and manipulating thin objects through the flip-and-pinch task. These changes to the hand enable it to utilize the table surface to establish and maintain a set of quasi-static constraints that guide the object through a very repeatable trajectory. Like power-grasping with adaptive hands, the flip-and-pinch task can be accomplished by the modified SDM Hand for a range of object dimensions with the same open-loop control input. By intelligently configuring the hand with respect to the table surface, this task maximizes the use of the fingers' adaptability in obtaining a static grasp on thin objects while minimizing the undesirable qualities of underactuation in producing a repeatable trajectory. This paper shows that it is possible to tweak design parameters to augment an underactuated hand's manipulation of small objects and suggests that other design changes can enable simple hands to accomplish other more dexterous manipulation tasks.

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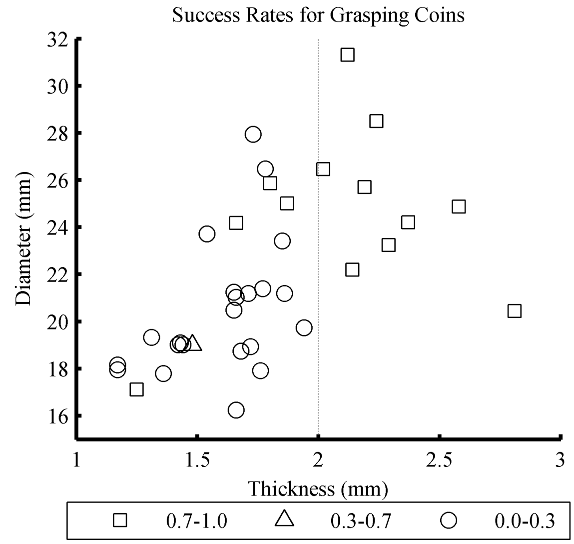

Fig. 12. Grasping success rates for a variety of coins, arranged by diameter and thickness. All coins thicker than 2 mm could be grasped at a 70% success rate or better.

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