Open-Loop Precision Grasping With Underactuated Hands Inspired by a Human Manipulation Strategy

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***Abstract*—In this paper, we demonstrate an underactuated finger design and grasping method for precision grasping and manipulation of small objects. Taking inspiration from the human grasping strategy for picking up objects from a flat surface, we introduce the flip-and-pinch task, in which the hand picks up a thin object by flipping it into a stable configuration between two fingers. Despite the fact that finger motions are not fully constrained by the hand actuators, we demonstrate that the hand and fingers can interact with the table surface to produce a set of constraints that result in a repeatable quasi-static motion trajectory. Even when utilizing only open-loop kinematic playback, this approach is shown to be robust to variation in object size and hand position. Variation of up to 20° in orientation and 10 mm in hand height still result in experimental success rates of 80% or higher. These results suggest that the advantages of underactuated, adaptive robot hands can be carried over from basic grasping tasks to more dexterous tasks.**

***Note to Practitioners*—This work was motivated by the need for a means for robots operating in unstructured environments to robustly grasp and manipulate a wide range of objects using a multipurpose hand. To date, one of the most difficult tasks for a general-purpose hand has been grasping small, thin objects, which are typically found resting on a flat surface such as a table. The size of the object and the presence of the backing surface make it difficult to establish contact with the object resulting in a stable grasp. In previous work, we have shown how proper attention to the passive mechanics of the hand, including mechanical compliance and underactuated differential transmissions, can enable robust, open-loop "power" grasping of large objects. In this paper, we extend the same concept to "precision" grasping of small objects with the same demonstrated robustness and simplicity.**

***Index Terms*—Compliant mechanism design, dexterous manipulation, human-inspired, underactuated grasping.**

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], the MARS and SARAH hands [2], and the 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 constraints between the hand and object create a stiff enveloping grasp, effectively assembling the object to the end of a manipulator.

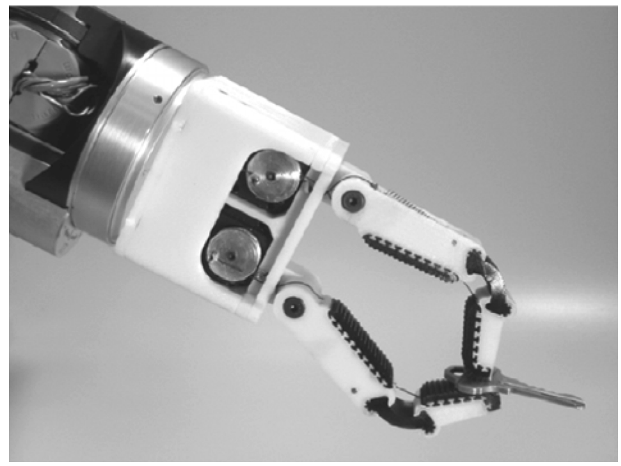

Fig. 1. A thin object, such as a key, must often be reoriented during the grasp acquisition process. Consequently, in-hand manipulation is critical to the operation of any dexterous robot hand.

The same design features that enable robust, adaptive power grasping would seem to make precision grasping and in-hand manipulation more difficult. Rather than using active control of grasp forces to constrain a grasped object, underactuated hands rely on hand-object contacts made while grasping to fully constrain the object to the end of a manipulator. A small object, such as the key shown in Fig. 1, will not contact a large enough number of finger links 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 naturally reduces its 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 [8]. Nonetheless, in-hand manipulation is possible with an underactuated hand, in the right circumstances. The authors have previously shown that an underactuated hand is capable of moving objects along minimum-energy trajectories, provided that the frictional contact constraints can be maintained passively by the underactuated mechanism [9]. By respecting the physics of manipulation tasks, surprisingly dexterous behaviors can emerge from an underactuated hand.

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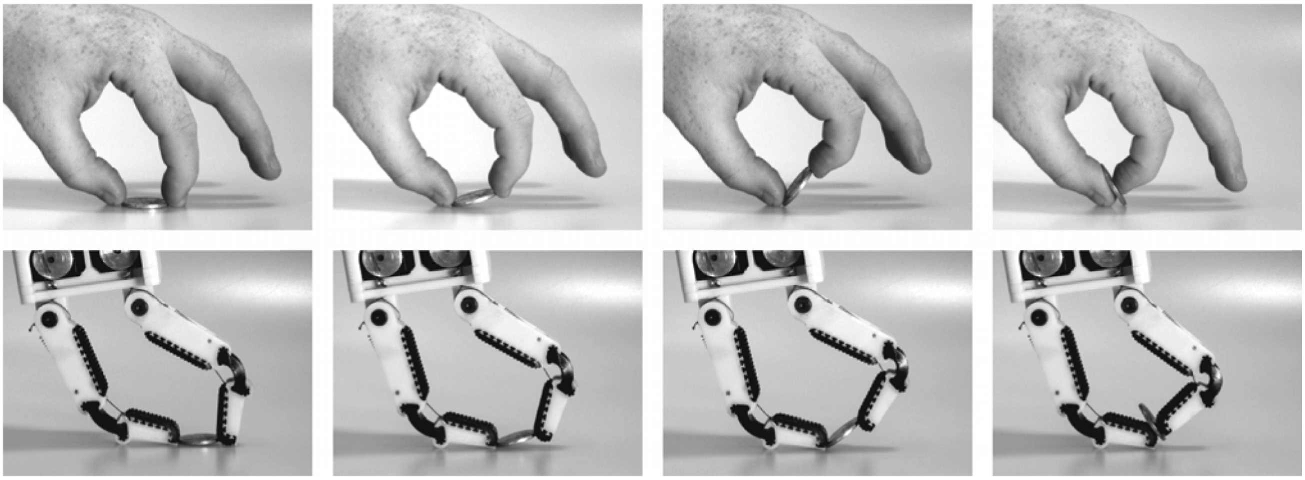

Fig. 2. The task described in this paper, flipping a thin object up to acquire a pinch grasp, was inspired by the human hand. Below, the authors' underactuated hand demonstrates the same procedure using kinematic playback.

This paper demonstrates a robot hand implementing a common primitive manipulation operation: 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 robotic 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. 2. The approach involves the use of a compliant, underactuated finger pair whose design is based on previous work by the authors [4], [9]. Much of what has been published on primitive fingertip manipulation tasks assumes that fingers need high-fidelity force control in order to stably manipulate objects, in combination with precise kinematic control of the fingertip position [11]–[15]. In contrast, the hand presented in this paper has no tactile sensors whatsoever, and relies only on rigid position control of the finger tendons to control the pose of the hand. Instead, the internal forces on the manipulated object are determined by the passive elastic elements in the hand and by the kinematic constraints due to wrist position and contact with the environment. We will show that the passive forces exerted by the hands on the manipulated object are sufficient to maintain a stable grasp throughout the trajectory, and that the motion of the object is kinematically determined, eliminating the need for complex planning or control algorithms. A preliminary report of the experimental results in this paper was submitted to the 2012 International Conference on Robotics and Automation [16]. The earlier paper focuses solely on the minimum thickness of object that can be grasped by the hand. This paper contains a much larger set of the experimental results, and entirely new analysis and experiments relating to uncertainty in the pregrasp posture of the hand.

This paper is organized into several sections. First, some preliminary experimental observations will be discussed, motivating the novel approach to the problem. The design of the underactuated fingers used in this paper will be introduced, and the human manipulation task will be translated into the robotic flip-and-pinch task. Second, the flip-and-pinch motion will be analyzed using a simplified linkage model, 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 ability of the hand to pick up thin objects and other common small, difficult-to-grasp objects from a flat surface. Parametric uncertainty will be examined by varying the pregrasp posture of the hand, so that the region of stability for the task can be determined.

II. Task Description

A. The Flip-and-Pinch Task

Fig. 2 (top) depicts the familiar process of a human hand grasping a coin from a table. The thumb is planted on one side of the coin, pinning it 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 authors hypothesized that this manipulation task can be performed reliably because the kinematics of the hand, governed by contact with the table and the prepositioning of the wrist, move the object along a trajectory that is passively stable. To test this, a robotic hand, shown in Fig. 2 (bottom), was used in a similar fashion to pick up the same coin. Prepositioning the robot hand to the side of the object, as the human did, the stationary finger (hereafter called the thumb) was moved up to the edge of the object. The opposing finger was then swept along the surface of the table by pulling on the actuator tendon, lifting 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. The motion of the hand during this process was constrained so that the fingers followed motion much like that of a four-bar linkage, as shown in Fig. 3. Many repeated experiments demonstrated that the same kinematic trajectory for the actuators (planting the thumb and then sweeping the finger into a pinch configuration) was capable of grasping a variety of objects, such as those shown in Fig. 4, having different thicknesses and widths, without altering the trajectory of the finger

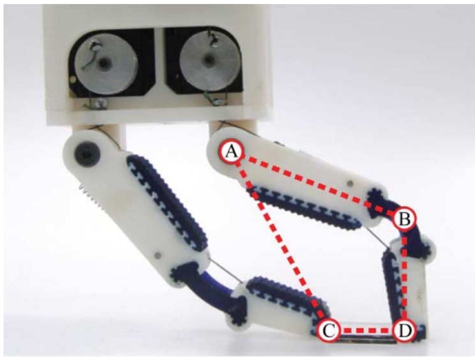

Fig. 3. The motion of the hand was observed to occur only within the four-bar linkage ABCD, because the wrist was held fixed, and the thumb was constrained by contact with the table.

Fig. 4. A wide range of objects could be picked up repeatably using the same feed-forward manipulation primitive.

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 retracting the actuated tendon at a constant rate.

B. The Robot Hand

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. Fig. 5 depicts the finger geometry. The proximal finger joint is a pin joint, having a parallel antagonistic spring; the distal joint is a flexure hinge. 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 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 [3]. 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.

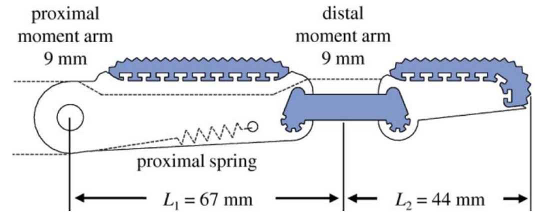

Fig. 5. The two-link fingers used for this experiment had a proximal pin joint and a distal flexure joint. The distal moment arm (distance from the tendon to the flexure centerline) was designed to match the 9 mm radius on the proximal joint pulley.

To build the planar hand used for this study, two of these fingers were arranged in an opposed configuration, having proximal finger joints located 52 mm apart. Each finger was independently actuated by a single Robot is 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, position control was used to hold the wrist in the Cartesian workspace, and the two finger tendons were driven on predetermined point-to-point motion trajectories using proportional-differential control.

C. Summary

So far, an underactuated hand has been used to perform a dexterous task by copying the corresponding human posture. Why this works remains to be shown; proceeding sections of this paper will answer this question, and further to quantify the range of uncertainty under which this primitive manipulation task is successful.

III. Analyzing the Flip-and-Pinch Task

The experimental observation that a manipulation operation can be performed repeatably using a sensorless, underactuated hand can be explained in this case by considering the constrained motion of the hand and object as they have been configured for the flip-and-pinch task. The object, pinned by the thumb against the table, rotates upward into the hand because the wrist, thumb, and active finger form a four-bar linkage, as previously mentioned. This linkage has only a single degree of freedom, and a single actuator whose motion will consequently move the object through a constrained trajectory of configurations. Because the actuation in the hand is nonredundant, the single actuator will not be enough to control both the force and the position of the grasped object. However, the passive elastic elements in the finger joints will determine the magnitude of the joint torques in the fingers at each configuration. If, therefore, these forces result in stable grasps as the object is flipped into the hand, the manipulation procedure does not need to rely on tactile sensing or force control.

In this section, we will examine a simplified model of the flip-and-pinch process that shows how the passive elastic elements in parallel with the finger joints ensure that the internal forces on the thin object are positive. The conditions under which these internal forces lie within the friction cone of the fingertip contacts will be examined, and design features to improve the passive stability of the hand will be suggested.

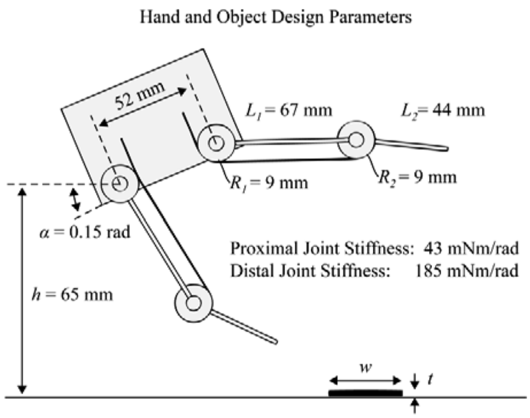

Fig. 6. The model used to analyze the behavior of the hand. The parameters h and α describe the wrist position and attitude during the task; the finger joint angles are represented by a vector θ.

A. Model

To predict the forces on a thin object picked up off the table, an approximate linkage model of the hand was constructed, as seen in Fig. 6. The flexures at the distal joint of each finger were treated as pin joints, so that each finger was equivalent to the two-link case of Hirose's Soft Gripper [1]. Because this is a well-studied class of mechanisms in the context of both underactuated fingers (e.g., [17]) and manipulation (e.g., [18]) the generality of the explanation is best ensured by making this approximation. The pin joint simplification will have some effect on the accuracy of the model, largely by ignoring the translational compliance of the distal link. However, these higher order effects will not alter the first-order behavior of the joint, which rotates in the plane. The configuration of the fingers was represented by a vector of joint angles, θ. The configuration of the hand at equilibrium was found by computing the energy of the hand and object, then minimizing subject to the constraints on the system. The joint elasticity was chosen based on the measured stiffness of each joint on the robot fingers, 44 mNm at the proximal joints and 185 mNm at the distal joints. The potential energy of the hand in mJ was expressed as a quadratic form using the stiffness matrix $\mathbf{K}$

$$V\theta = \frac{1}{2}\theta^T\mathbf{K}\theta = \frac{1}{2}\theta^T \begin{bmatrix} 44 & 0 & 0 & 0 \\ 0 & 185 & 0 & 0 \\ 0 & 0 & 44 & 0 \\ 0 & 0 & 0 & 185 \end{bmatrix} \theta. \qquad (1)$$

The length of the actuated tendons in mm, $A(\theta)$, was found by multiplying the joint angle vector by a moment arm matrix $\mathbf{R}$

$$A(\theta) = A_0 - \mathbf{R}\theta = A_0 - \begin{bmatrix} 9 & 9 & 0 & 0 \\ 0 & 0 & 9 & 9 \end{bmatrix} \theta. \qquad (2)$$

Here, A_0 is a constant representing the length of tendon between the fingers when the fingers are fully extended. Actuation was modeled by constraining (2) to be equal to or less than some vector of actuator positions u

$$C_{\mathrm{act}}(\theta) = A_0 - R\theta \leq u. \qquad (3)$$

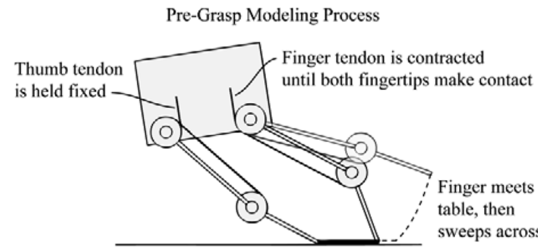

Fig. 7. The pregrasp hand configuration was computed by finding the minimum energy configuration in which the fingertips initially touch the grasped object. The table top was modeled as an inequality constraint.

The fingertip positions were computed from the finger kinematic equations as $x_F(\theta)$ and $x_T(\theta)$, standing for "finger" and "thumb," respectively. These points were constrained so that they were unable to penetrate the surface at $y = 0$

$$C_{\mathrm{surf}}(\theta) = [\, x_F(\theta) \quad x_T(\theta)\,]^T e_y \geq \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \qquad (4)$$

B. Finding the Pregrasp Hand Configuration

In order to find the hand configuration in which the object is pinched but still in contact with the table (shown in Fig. 7), the equilibrium configuration of the hand was computed by minimizing the energy $V(\theta)$, subject to the tendon constraints from (3) and the tabletop constraints from (4). Starting from some initial configuration above the table, the thumb tendon was held fixed, while the finger tendon was contracted. The tip of the finger hit the table, and swept across, until the distance between the fingertips on the table was equal to the object width, w. Once contact was made, the object was modeled as a rigid link connecting the two fingertips. Because it is difficult to exert a contact moment on a thin object held by the edges, pinned constraints were applied to the fingertips, leaving the object with only one degree of freedom representing the rotation of the object ψ

$$C_{\mathrm{tip}}(0, \psi) = x_F(0) - x_T(0) - w \begin{bmatrix} \cos\psi \\ \sin\psi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \qquad (5)$$

From this computed pregrasp configuration, the mechanics of the flip-and-pinch motion was modeled by minimizing the potential energy of the hand with respect to θ and ψ, subject to the constraints $C_{\mathrm{tip}}(\theta, \psi)$, $C_{\mathrm{surf}}(\theta)$, and $C_{\mathrm{act}}(\theta)$. The minimization was performed for the studies presented here using Matlab's optimization toolkit.

C. Passive Fingertip Force Results

By contracting the finger tendon from the pregrasp configuration, the motion of the grasped object was computed. Forces on the object were found by examining the Lagrange multiplier values for the minimum-energy solutions. The magnitude of the predicted contact forces for an object having width $w = 35$ mm is shown in Fig. 8 for a range of object orientations from $\psi = 0$ to $\pi/2$ radians. Results for a range of object widths are tabulated in Table I, and show that the internal forces on the object lie in

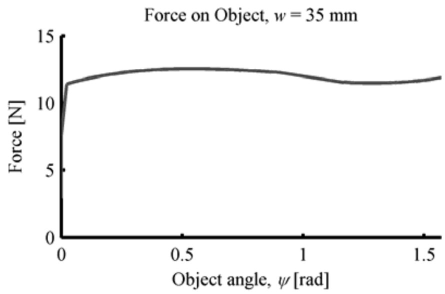

Fig. 8. The internal force on the grasped object is relatively constant as it is rotated upwards into the hand.

TABLE I
CONTACT FORCE AND GEOMETRY, $0.1 < \psi < 1.6$

Obj. Width [mm]	Min. Force [N]	Max. Force [N]	Avg. Force [N]
15	9.24	13.74	10.63
20	9.66	13.30	10.77
25	10.23	13.28	11.20
30	10.84	12.76	11.61
35	11.49	12.52	12.02
40	10.34	13.15	12.41

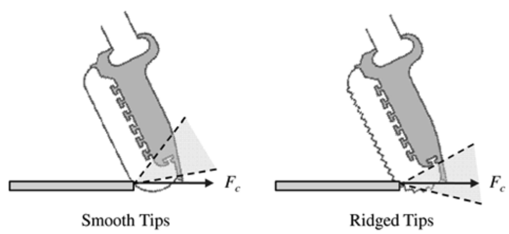

Fig. 9. The ridges of the tips of the fingers are there to provide more favorable contact normal vectors for thin objects. Stability is improved by aligning the friction cone with the contact force on the object.

a relatively narrow range between 9–14 N, for any object orientation larger than 0.1 rad. The direction of the internal force was always found to be directly in line between the two contact points on the object, which is expected if the contact constraints between the fingers and the object behave as pinned constraints.

In order to ensure that reliable frictional contact can be made between the fingertips and the object, some design considerations must be weighed. We observed that it was difficult to obtain a consistent contact when the object is lying flat on the table. This can be explained by the adverse contact geometry one might anticipate for a large fingertip meeting a thin object, illustrated in Fig. 9. The object force, which as previously mentioned must lie parallel to the object as the object is lifted off the table, must also lie within the friction cone. On a smooth fingertip, the friction cone will be centered on the normal to the fingertip surface. Rather than using an extremely sticky fingertip to increase the angle of the friction cone, small ridges were added to the pads of the fingers. These ridges have the effect of creating many small facets on the fingertip surface, which were able to catch the edge of the object and present a more favorable initial contact angle for picking up the object.

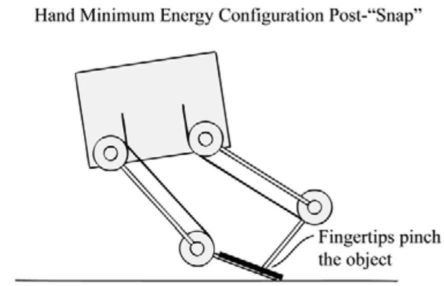

Fig. 10. Once the object has rotated completely into the hand, the fingers will snap into a pinching configuration if contact with the object is suddenly lost.

D. Loss of Contact and Transition to Pinch Grasp

Breaking the contact constraints on the object is also critical to the success of the flip-and-pinch grasp acquisition process. When the grasped object is in a nearly vertical configuration, the object must break free from the active finger so that the fingertips can close about the long sides of the object. This breaking point is the point at which the contact force on the object leaves the friction cone, and is determined by the rotation of the object relative to the hand and the contact normal vector of the fingertip. The angle at which contact is lost was found to be experimentally repeatable, although the linkage model does not attempt to capture the exact point of release, due to the ridged finger surface and the compliance of the finger pads. Any attempt to define a direction normal to the fingertip at the point of contact would require in-depth modeling of the surface mechanics, and this modeling is otherwise unnecessary for understanding the task. However, the postcontact configuration of the fingers is easier to predict with the linkage model given an experimentally determined breaking point. Once the fingertip constraint with the object is broken, the finger quickly snaps to its equilibrium configuration against the other finger, as seen in Fig. 10. This new minimum energy configuration can be found by assuming that the fingertip is free to slide against the thumb without much friction. The trajectory of the finger tendon was chosen so that the two fingertips remain in contact after the snap, rather than moving past each other and slipping off the object's surface. Once the object is in a pinch grasp, both the finger and thumb tendons can be tightened further by contracting a few millimeters to increase the normal force on the pinch grasp. The stability of this post-manipulation underactuated pinch grasp is reported in [19].

E. Summary

In this section, we have shown that active fingertip position control is not needed to manipulate an object, if the constraints between the hand, the object and the environment can be used to kinematically determine the motion of the hand in a way that is desirable. We have also shown that force control is not needed to maintain stability during manipulation, if the elastic elements in the hand produce internal forces on the grasped object that satisfy the necessary conditions for frictional contact. This is not particularly surprising, as series elastic actuators have long been

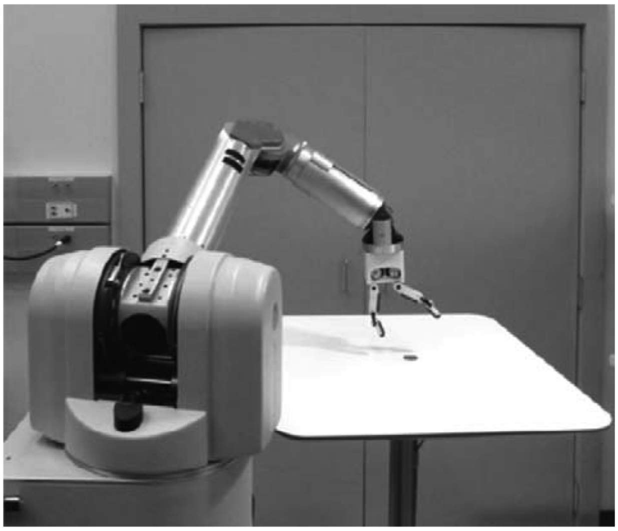

Fig. 11. The Barrett WAM and two-fingered robot hand used for experiments.

acknowledged as a mechanism for improving manipulation performance through passive mechanisms [12]. This analysis provides an example of another successful active-passive actuation scheme.

IV. Experimental Validation

To quantify the range of parameters over which the flip-and-pinch procedure remained stable, systematic experiments were performed. The hand was mounted on a 7-DOF Barrett Whole-Arm Manipulator (WAM), shown in Fig. 11. Four key parameters were identified from the modeling of the procedure: The width w and thickness t of a grasped object, and the wrist height h and angle α, as defined in Fig. 6.

A. Minimum Object Dimensions

The first experiment performed was designed to ascertain the thinnest object that the hand is capable of picking up off a flat surface. International coins were used as a set of test objects, varying in thickness between 1 and 3 mm and in width between 16 and 32 mm. For these tests, the wrist was held at a height of $h = 71\ \mathrm{mm}$ and a wrist angle of $\alpha = 0.05\ \mathrm{rad}$. Ten trials were run on each coin. This initial experiment was conducted to determine the lower bound for the thickness of objects that the hand could reliably grasp while maintaining the fingertip frictional constraints, as discussed in Section III-C. Through this initial test, the authors also determined that the object can initially be placed at any point between the thumb and active finger, and that the actuation of the fingers can be run at any speed without discernible changes to the rate of success.

B. Robustness to Error

The second experiment explored the effect of varying pregrasp poses to determine the effect of height and orientation error on the success rate. In these experiments, a series of trials were run on a variety of objects at several different hand height and angle combinations.

The hand height is measured from the base of the thumb, and the angle offset is the deviation from the horizontal, as detailed in Fig. 6. The lower bound value of 65 mm for height was chosen as the height where the distal link of the thumb is pinned flat against the table surface. Any value of h below this was found to tip the distal link of the thumb up from the table surface, resulting in failure.

TABLE II
Experimental Parameters

Parameter	Min. Value	Max. Value	No. of samples
Thickness, t	3.20 mm	4.78 mm	2
Width, w	15 mm	30 mm	4
Height, h	65 mm	80 mm	4
Angle, α	0.05 rad	0.4 rad	8

The wrist angle α relative to the table and height h above the table were set using the inverse kinematics of the WAM. The range of t, w, h, and α chosen for the second experiment are shown in Table II. A total of 256 parameter combinations were tested, with ten trials for each combination to obtain a success rate. A trial was considered a success if the arm could be moved after grasping without dropping after the grasp was acquired. The reference trajectories for the servos controlling finger tendon excursion were kept the same for all trials. The resulting success rates reflect the system's robustness to not only object placement along the surface, but also errors in wrist positioning.

V. Results and Discussion

A. First Experiment: Object Thickness

Fig. 12 shows the results of this study for 37 coins in the initial experiment, with diameters between 16–32 mm and thicknesses between 1–3 mm. Despite the use of the same hand trajectory regardless of coin size and purely open-loop playback, the hand demonstrated a success rate of 70% or higher (and in most trials 100%) for all coins having 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. This was observed to be caused by poor frictional contact between the fingertip and the edge of the object, as discussed in Section II-C. Specifically, fabrication constraints limited the minimum size of the fingertip ridges, and consequently limited the finger's effectiveness in aligning the friction cone past this point.

The authors also noticed another failure mode for acquiring contact, as the coin thickness approached the thickness of the "fingernail" on the back of the thumb. In some cases, the object was seen to slip up between the nail and the pad, wedging the coin into the thumb but angling it downward at the other end, so that the active finger slipped over the edge of the coin. Careful redesign of the fingernails might address this issue.

B. Second Experiment: Wrist Posture

Figs. 14–18 show the results of the analysis on the pick-and-pinch task in the second experiment. The wrist height h was the most important parameter in determining the success of a grasp, due to the need for stability in the thumb constraints. In general, a smaller angular offset and lower height led to greater success. Minimizing these two parameters increased the stiffness of the thumb, making it easier for the hand to maintain the requirements of the quasi-static four-bar configuration.

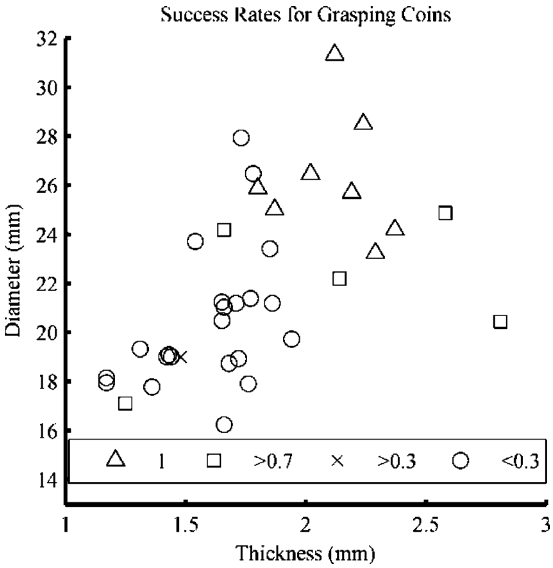

Fig. 12. Grasping success rates for a variety of coins, arranged by diameter and thickness. All coins thicker than 2 mm could be grasped at a 70% success rate or better.

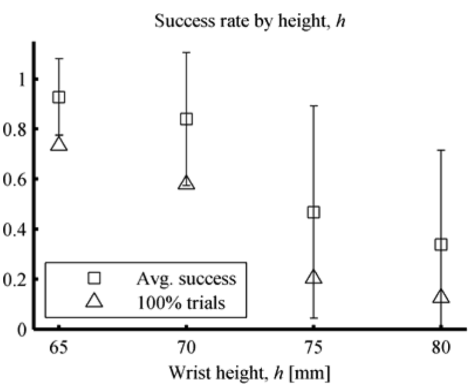

Fig. 13. Grasping success rate with respect to height h.

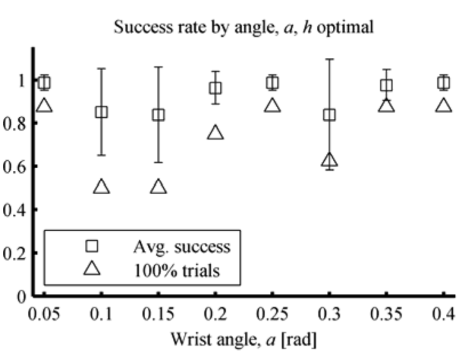

Fig. 14. Grasping success at optimal height h (65 mm) with respect to wrist angle α.

In order to independently discover the effect of variation in h and α, the data for all trials having an optimal height of 65 mm were separated and displayed in Figs. 14 and 15. They show that the success of the task was not sensitive to the angle α over the range of values tried in this experiment. Fig. 15 shows that the mean success rate is fairly consistent at the experimentally observed optimal height of 65 mm for different values of angle offset and object width. However, an upper bound on α was

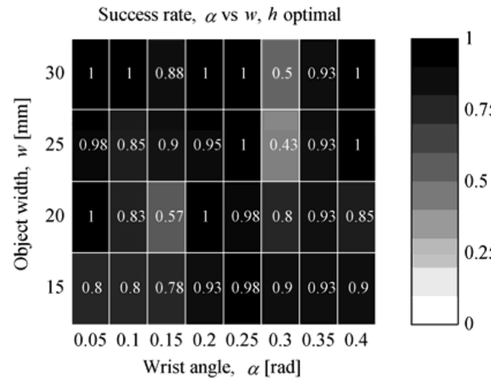

Fig. 15. Grasping success at optimal height (65 mm) for various angle α and object width w combinations.

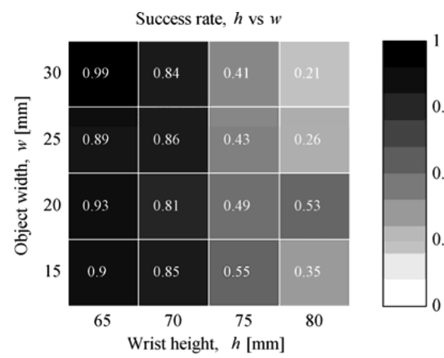

Fig. 16. Success rate for combinations of height h and object width w.

observed as the palm was rotated away from the tabletop. At some angle above 0.4 rad, the active finger ceased to make contact with the table before meeting the edge of the object. Wrist height also impacted the width of object that could be grasped. Fig. 16 shows the general trend between wrist height and object width for all of the trials. The object width did not have a significant correlation with wrist height in determining the success or failure of a grasp. Instead, failures at large wrist heights were due primarily to the fingers having insufficient support against the tabletop; fingers in these configurations flexed or slid against the table rather than firmly pinning the object. The limited stiffness in the position control of the WAM wrist was also observed to have some effect on optimal wrist height, as the contact between the fingers and the table was observed to push the whole hand upward momentarily during grasp acquisition. Thus, leaving some margin in the height above the table may be necessary for best results. Taking into account both pregrasp hand parameters, Fig. 17 shows that although 65 mm appears to be the overall best value of h, setting α equal to 0.05 causes the hand to perform just as well for all objects 20 mm or wider, at initial wrist heights up to 75 mm.

C. Summary

These experiments have demonstrated that the passive flip-and-pinch manipulation and grasping procedure is stable for a wide range of task parameters. Contact with the object can be reliably made with objects as thin as 2 mm, and the optimal wrist height of 65 mm can be varied by as much as 10 mm without reducing the rate of success. There is no distinct trend regarding

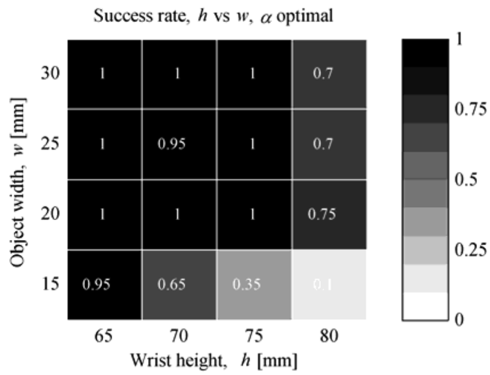

Fig. 17. Success rate at optimal angle α (0.05 rad) for various height h and object width w combinations.

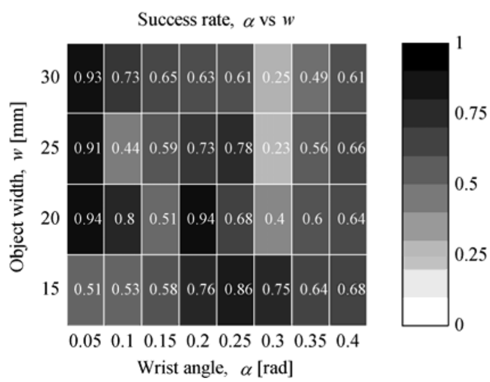

Fig. 18. Success rate for combinations of angle α and object width w.

stability over α for the optimal height, but minimizing α allows for significant variation in h.

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 shows that a fairly generic underactuated robot hand can be used to pick up small objects by choosing the correct starting posture. 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 in order to produce a repeatable trajectory.

These results suggest interesting future avenues of inquiry. Grasp or manipulation planning with underactuated hands is a young field, and a library of passive, underactuated manipulation primitives based on environmental affordances could possibly yield good results. Generalizing this relatively simple manipulation motion to other, more complex tasks through virtual linkage models may prove fruitful.

Acknowledgment

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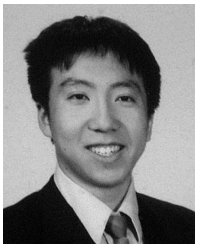

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