Object Picking through In-Hand Manipulation using Passive End-Effectors with Zero Mobility

Caio Mucchiani, Monroe Kennedy III, Mark Yim, and Jungwon Seo

Abstract—This paper presents a novel method for picking objects through quasi-static in-hand manipulation with end-effectors that have no degrees of freedom. Our stable manipulation/grasp planning is achieved with two contacts at fixed distance and the force of gravity, and is provably complete and correct. Practically, our robotic in-hand manipulation technique can facilitate low-cost manipulation and render simple end-effectors such as the parallel-jaw gripper more dexterous in picking, placing, and handing-off objects in case, for example, failing actuated grippers become frozen and it is impossible to exert sufficiently large internal forces. Our picking technique can also be applied to placing objects. Implementation and experimentation on a custom-made direct-drive manipulator and a conventional manipulator are presented. Many experiments were performed for both picking and placing and the results demonstrate usefulness of this method for manipulating a variety of common objects, with different geometries and surface conditions.

Index Terms—Grasping, manipulation planning, grippers and other end-effectors.

I. INTRODUCTION

We are concerned with robotic object picking through in-hand manipulation using end-effectors with no internal mobility. Fig. 1 depicts this scenario in which the robot is picking the cylindrical object with the non-functioning parallel-jaw gripper (thus no internal mobility). This lack of mobility implies that generally it can be impossible to (1) control contact positions and contact wrenches and (2) guarantee desired grasp properties such as force- or form-closure. While objects have been shown to be stable with just two frictionless contacts [1], transitioning from grasps to release such as picking up or placing an object can be complicated.

The proposed scenario can be practically important for low-cost robotic manipulation. Costs of robotic grippers are often determined by the number of actuators. End-effectors with no internal mobility will use zero actuators (and thus no actuator cost). The scenario is also closely related to the important issue of robotic dexterity. For example, consider the parallel-jaw gripper, which may be by far the mostly used robotic end-effector. Although parallel-jaw gripping can be stable (it is well known that a grasp of two contacts that oppose each other can resist any external wrench applied to the object), it is necessary to impart sufficiently large internal forces to secure the object. The typical failure modes of parallel-jaw grippers thus include: object slippage due to insufficient internal forces, object damage from too large internal forces, and inability to make two contacts opposing each other (for example, due to limited range of joint motion). A more adaptive approach that depends less on frictional forces (and in turn, internal forces) and exact contact positioning will address those issues and render robotic manipulation more dexterous and practical.

This paper presents a novel robotic in-hand manipulation technique for picking objects off a flat surface with an end-effector that can be abstracted as a collection of two point fingers with fixed separation distance. The end-effector thus lacks internal mobility and has to be controlled passively. The resulting operation incorporates tipping and regrasping as can be seen in Fig. 1. It will be shown how the object can be in static equilibrium with the two end-effectors contacting it but not necessarily oppose each other. We will also show our technique can be applied to a wide range of scenarios, for example, how it can complement the common parallel-jaw gripping by addressing the issues aforementioned. Our picking technique can also be directly applied to placing objects back
on a flat surface.

The paper is organized as follows. Sec. II outlines relevant literature. Sec. III formally states our proposed problem. Sec. IV presents our manipulation planning and discusses its properties. Sec. V presents experiments performed with a custom-made, direct-drive arm and a conventional manipulator. The conclusion is presented in Sec. VI.

II. RELATED WORK

A large variety of robotic object manipulation techniques have been developed to date. In [2], they are classified according to their models of task mechanics.

Kinematic approaches to robotic manipulation include robotic caging, concerning how to bound the mobility of objects of interest without necessarily making contact. Algorithms for computing cages were presented in [3]. The relationship between caging and grasping was formalized in [4] and it has been shown that caging can render robotic manipulation more robust [5].

One fundamental form of robotic quasistatic manipulation is robotic grasping and fixtures. The closure properties of robotic grasps have been investigated extensively. Important notions of grasp stability include force-closure, form-closure, and immobilization [6]. It has been shown that the dynamic stability of a grasp is a function of local contact geometry, contact models, and material properties [7]. Model-based algorithms for testing and constructing stable robotic grasps based on those notions were presented in [8], [9]. Data-driven approaches to grasp synthesis have also been a topic of interest [10]. Robotic pushing [11] is another practically important capability that can be achieved in a quasistatic manner. Recently, robotic systems that can do grasping/manipulation with some autonomy have been presented in [12], [13].

The work presented in the paper is relevant to such quasistatic object handling skills, particularly for nonprehensile manipulation. Examples in the literature include stable rotations of a polygonal object with two contacts [1], object handling with flat contact surfaces (or palm) [14], knocking an object over with a single contact [15], and pivoting operation [16]. However, these techniques cannot be directly applied to our problem. For example, compared to stably supported rotations [1], our problem is formulated with a more conservative assumption that the distance between two contacts is fixed. Our interest in keeping an object of interest within a gripper lies beyond the scope of the problem of robotic toppling [15].

Our problem is also relevant to robotic in-hand manipulation, which refers to the capability to move and hold an object within a robotic hand. This is an important problem related to the issue of robotic dexterity. We are particularly interested in rendering low degrees-of-freedom (DOF) end-effectors, such as the parallel-jaw gripper [17] or single rigid body end-effectors [18], more dexterous when it comes to object picking and placing. Robotic in-hand manipulation capabilities have been realized in the forms of robotic regrasping, dexterous manipulation, and finger gauging, and are an active research area [19]–[22]. Robotic in-hand manipulation is still a challenging problem, with a high-dimensional search space and limited robotic motor skills. The challenge task in the paper is also relevant to in-hand manipulation using resources from the environment, a topic also examined in [23].

Dynamic manipulation is a relatively new area. Some early examples of dynamic manipulation were demonstrated by a juggling machine [24]. More recent examples include dynamic nonprehensile manipulation for reorienting and picking [25].

III. PROBLEM DESCRIPTION

The problem we address in the paper is concerned with the planning and control for quasistatic object picking. We assume that the target object is initially placed on a flat surface and the direction of gravity is normal to the surface. Our end-effector is assumed to provide two contacts, as the common parallel-jaw gripper. Unlike parallel-jaw gripping, however, we are interested in more conservative scenarios in which it is impossible to control the distance between the two end-effector contacts, and thus unable to squeeze objects and attain force-closure grasps. Our aim is to develop a method for picking objects through quasistatic in-hand manipulation with such simple end-effectors as depicted in Fig. 1. This can be practically important in case, for example, failing actuated grippers become frozen and it is impossible to exert sufficiently large internal forces (consider gripping a slippery, cone-shaped object with a parallel-jaw gripper).

The proposed scenario involves three contacts: two contacts with the end-effector plus one contact with the environment (Fig. 2(a)). According to screw theory [26], one approach to attaining static equilibrium with the three resultant contact wrenches and the wrench of gravity is to keep them necessarily coplanar. Motivated by this, we shall investigate the problem of object picking on the plane as described in Fig. 2(b) in which the target object is a rigid polygon, moving on the plane, and placed stably on a flat surface, modeled as a sufficiently long line segment. An end-effector is then abstracted as a collection of two contact points whose distance is fixed; thus it is unable to squeeze an object by itself. Contacts on the object are modeled as point contacts with friction [27]. We will investigate how to pick the object off the ground by manipulating it with the simple end-effector that has no mobility. We are interested in keeping the object stable within the end-effector, that is, between the two contacts, during the
picking operation although some strong notions such as form-closure will not be attainable due to the lack of mobility and sufficient number of contacts. Our goal state features a stable grasp under the influence of gravity. We shall also consider how to generalize the resulting planar operation to three-dimensional picking problems.

IV. TIPPING, REGRASPING, AND PICKING WITH TWO CONTACTS AT FIXED DISTANCE

This section presents our manipulation planning for the planar picking problem described in Sec. III. Our approach features three types of atomic operations. We arrange these operations into a feasible manipulation plan for object picking. We also discuss the properties of our manipulation planning.

A. Atomic Operations

We first present three types of atomic operations concerned with tipping polygonal objects over under the influence of gravity, with an end-effector making a nonantipodal contact pair at fixed distance. Without loss of generality, we assume that the objects rotate counterclockwise (CCW).

Type I Tipping: With a nonantipodal contact pair, our end-effector can make two types of grasps in terms of the sign of the moments it can exert (see Lemma 1). For example, as can be seen in Fig. 3(b), the moment of the contact force couple at $C_1$ and $C_2$ can point in the positive (negative in Fig. 3(d)) z-direction. In Type I Tipping, the object is tipped CCW by the grasp that can impart positive z-directional moments (Fig. 3(b)).

Type II Tipping: In Type II Tipping, the object is tipped CCW by the grasp that can impart negative z-directional moments (Fig. 3(d)).

Regrasping: In Regraspersing, the end-effector is rotated about one of the contact points. As a result of the regraspersing, the sign of the moment of the contact forces switches. These operations are exhaustive in terms of the relative position between the object's center of mass (CoM) and the vertex about which it rotates, as will be explained in the following subsection.

B. Planning for Picking

The progress of our planning shall be explained using Fig. 3 where the object rotates CCW monotonically, without loss of generality.

The first step is to determine where to make contacts and how to acquire the contacts (Fig. 3(a)). As in parallel-jaw gripping, our end-effector is supposed to make two point contacts on an object's edge pair where it is possible to have an antipodal grasp, whose two contacts can see each other by a line inside both friction cones [28]. Such an edge pair (for example, a parallel edge pair) can be found by a combinatorial search in $O(n^2)$ time for an n-sided polygonal object [17]. The two contact positions on each edge are selected so that their distance equals to $\delta$, the distance between the two contact points of the end-effector. The end-effector is then position-controlled to follow a feasible path into the contact positions.

Next, the atomic operations are performed sequentially to roll the object CCW until the inward pointing contact normal at the contact $C_1$ is antiparallel to the force of gravity (Fig. 3(e)). The position of the object's CoM relative to the contact normal at the ground contact determines which action to take. If the CoM is on the right (left) half plane delimited by the contact normal, as illustrated in Fig. 3(b) (Fig. 3(d)), the end-effector is controlled to perform Type I Tipping (Type II Tipping). If the CoM is on the line of the contact normal (Fig. 3(c)), the end-effector is controlled to perform Regrasperg from grasp $\{C_1, C_2\}$ to $\{C_1, C_2'\}$. If other edge of the object hits the ground in the meantime, the motion proceeds with the new pivot (see the pivot changes from $P$ to $Q$ between Fig. 3(c) and (d)). Thus, during the whole manipulation process the pivot can switch at most $n$ times for an n-sided polygonal object. Finally, at most one Regrasperg may be needed in order to properly counteract the moment of gravity before lifting the object: for example, between Fig. 3(d) and (e), the grasp has changed from $\{C_1, C_2\}$ to $\{C_1, C_2'\}$ before the lifting-up happens.

During the tipping and regrasperg operations and upon the termination of the process, the contact forces can properly counteract gravity; thus the object remains in static equilibrium (see Lemma 1). The manipulation process should terminate and can be applied to any polygonal shape that admits antipodal grasps (see Lemma 2). Because two distinct poles of rotation (one for the tipping, the other for the regrasperg) suffice for the operations, it is possible to implement the picking process using a position-controlled robot arm with two DOF. Two types of implementation can be considered: reactive control based on force feedback and deliberative control by planning in advance (see Sec. V).

C. Discussion

The following lemma shows that the object remains in static equilibrium during the manipulation; thus it is possible to execute the picking operation in a quasistatic manner.

Lemma 1. During the manipulation process stated in Sec. IV-B, an object can be in static equilibrium with two point contacts on an edge pair that can accommodate antipodal grasps.

Proof. First, we will check for static equilibrium during the tipping operation. If the two end-effector contacts are antipodal, they form a force-closure [27] grasp that can be in static equilibrium. Otherwise (with two nonantipodal contacts), the two contacts alone cannot be in force-closure because they fail to be in torque-closure [29], that is, the moments of the two contact forces are necessarily unilateral and the sign is determined by their relative position. Still, the two contacts are in force-direction closure [29], where the contact wrenches span the space of all forces. No matter where the contacts are located on the edges, the condition of force-direction closure is invariant. According to the description of Type III Tipping, the signs of (1) the moment of gravity with respect to the pivot and (2) the moment of the contact force couple are always opposite. Therefore, the system of all wrenches can
be in torque-closure and this in turn implies force-closure and possibility of static equilibrium.

Second, during the regrasping, the ground contact and one of the two end-effector contacts are able to exert wrenches counteracting the wrench of gravity. In Fig. 4(a), the friction cones define a band (see the orange set) between the two supporting hyperplanes (parallel to the direction of gravity) of the two convex regions that are the composite wrench cone. As long as the line of the force of gravity remains in the band, the object can be in static equilibrium. The finite size of the band implies the regrasping operation can be performed with some robustness in the actual orientation of the object.

Third, at the terminating condition, the line of the contact normal at $C_1$ is supporting the composite wrench cone because it is delimited by the edges of the friction cone at $C_1$ (Fig. 4(b)). At the same time, the contact normal is parallel to the wrench of gravity. Therefore the wrench of gravity can be spanned by the composite wrench cone.

By taking advantage of frictional contact forces, the whole process can actually be terminated before the terminating condition is satisfied exactly. This is because the composite wrench cone is pointed at $C_1$ as can be seen in Fig. 4(b). Therefore the contact normal at $C_1$ does not have to be necessarily parallel to the force of gravity. During the tipping operations, if the center of rotation of the end-effector is on the pivot ($P$ or $Q$ in Fig. 3), then it is possible to tip over the object with no sliding. If the pole is off the pivot, the object will slide both on the ground and the end-effector while tipping over; contact mode analysis shows that it is feasible without losing static equilibrium. While it is possible to tip over an object with only one point contact, with two contacts it is possible to rely less on frictional forces and exact contact positioning as discussed in the proof of Lemma 1. In contrast, in one-contact object tipping, friction and contact positioning is critical [15]. In our two-contact manipulation, it is also possible to retain the object within the end-effector, which is impossible with only one contact.

The following lemma shows that the picking operation can be applied to a wide range of shapes.

**Lemma 2.** The manipulation process stated in Sec. IV-B terminates for any polygonal shape that admits antipodal grasps.

**Proof.** A polygonal object is in contact with a sufficiently large flat surface only at the vertices on its convex hull. Therefore the object keeps turning CCW by the manipulation process of Sec. IV-B because it is impossible for concave vertices to make contact with the surface. The angle between the contact normal at $C_1$ and the force of gravity changes monotonically and thus the motion terminates.

Departing from the two-dimensional polygonal object model, our technique can be applied to three-dimensional objects by effectively suppressing the motions off the plane, for example, using curved fingers as investigated in our previous work [18]. This point shall be demonstrated in the next section with experiments performed with essentially prisms and objects with rotational symmetry, a class of object shapes which may be of industrial importance.

Our object picking technique can also be applied to object placing, by reversing the picking motion in a quasistatic manner. In the next section, we will demonstrate not only picking but also placing experiments.

The lemmas above imply that our object picking technique with the passive, zero mobility end-effector model can be as complete as two-dimensional parallel-jaw gripping in the
sense that it can be executed by two contacts on an edge pair accommodating parallel-jaw grasps (that is, antipodal grasps). Our method can also generalize the way we use the common parallel-jaw gripper by (1) not depending on antipodal contacts (thus no need to search for feasible antipodal grasps and less sensitive to sensing/positioning accuracy), (2) not squeezing the objects (thus no need to control contact/friction forces), and (3) adapting the shape of the gripper fingers. Our approach can thus be applied even to a failing parallel-jaw gripper, which is not able to squeeze objects, to do successful object picking. But, the object may roll on its convex hull until the tipping operation terminates and the regrasping actions will need sufficiently large free space, which can render end-effector accessibility/reachability check harder than parallel-jaw gripping.

V. IMPLEMENTATION AND EXPERIMENTATION

We demonstrate the effectiveness of our technique using a custom-made direct-drive arm capable of joint torque sensing and our state machine software built upon the model of mechanics discussed in Sec. IV. Sec. V-A introduces our hardware and software system and Sec. V-B presents our experiments for object picking and placing performed with the direct-drive arm. The state machine software enabled the arm to transition between Type I/II Tipping and Regrasping actions in an autonomous manner through joint torque feedback. We also present experiments with a conventional 7 DOF manipulator in Sec. V-C.

A. Direct-Drive Arm: Hardware and Software

![Fig. 5. (a) CAD exploded view showing two motors, a parallelogram linkage (the black links), and two white rigid body fingers constituting a zero DOF end-effector. The motor axes are collinear. (b) Completed hardware setup.](image)

We developed a two DOF arm using a parallelogram five-bar linkage with a closed-loop kinematic chain (Fig. 5); similar approaches can be seen in [30]. Its two DOF motions are composed of one DOF internal deformation and the rigid body rotation of the parallelogram itself. The links are laser-cut ABS plastic. 3D-printed, single rigid body fingers can be attached to the arm linkage using mechanical adapters. We employ direct-drive actuation. Two iPower GBM6212H-150T brushless DC motors (torque limit: 0.5Nm) are directly coupled to two links of the parallelogram linkage, with no gearbox. If the two motors, denoted $M_1$ and $M_2$ (Fig. 5(a)), spin with the same angular velocity, the parallelogram linkage performs rigid body rotation. If $M_2$ spins solely, the parallelogram is deformed. The motors are controlled by IQinetics IQ-MC-17-15-24C-H motor controllers\(^1\) with a high resolution position sensing capability—12 bits or 4096 counts per revolution. Our direct-drive arm is capable of reliable joint torque sensing with no explicit torque sensor [31], and thus enables low-cost, autonomous manipulation in a reactive manner. The torque on the motors is calculated from their current readings, with \pm20% estimated errors due to noise and friction at the joints. Serial communication with the motors is realized using FTDI USB to serial UART.

We developed MATLAB software for communicating with the motors and implementing functions for not only low-level torque calculation but also in-hand manipulation capabilities. The operation of our software can be explained using the abstraction of a finite state machine, also can be seen in [32]–[34], with the following four states:

- **Regrasp CCW**: The arm rotates the end-effector CCW about one of the two fingers.
- **Regrasp CW**: The arm rotates the end-effector CW about one of the two fingers.
- **Tip**: The arm itself rotates CCW.
- **Lift**: The arm translates the end-effector upward by deforming the parallelogram linkage.

The organization of these states can be customized to suit the purpose of experiments (that is, object picking or placing), as will be elaborated in the following subsection.

B. Experiments with the Direct-Drive Arm

![Fig. 6. Finite state machine for object picking. Its operation terminates in “Lift” state.](image)

1) **Object Picking**: Fig. 6 represents our software in the object picking mode, implementing the planning in Sec. IV-B. We need a precondition regarding the initial placement of the fingers that one of the two fingers is already in contact with the object. This is because our 2 DOF arm lacks sufficient mobility to address general path planning/trajectory following scenarios. This can be relaxed by using, for example, a conventional 6 DOF industrial arm. Given the precondition, the finite state machine of Fig. 6 is executed. First, in Regrasp CCW state the end-effector is rotated until the condition of edge label $A_0$ is satisfied (this is the moment when the other finger also makes contact with the object). Then in Tip state the arm rotates CCW until $B_0$ is satisfied (at this moment the CoM is on the line of the contact normal at the ground contact). Next, after the regrasping is done ($C_0$) in Regrasp CW state, the arm rotates CCW again in Tip state. If $B_1$ is satisfied, we

\(^1\)http://iqinetics.com/
enter Lift state. If the lifting operation is unsuccessful ($\mathcal{D}_0$), the state is transitioned to Regrasp CCW before attempting to lift again.

Those edge labels ($\mathcal{A}_0$, $\mathcal{B}_0$, and so on), called the state guard conditions, are formulated using (1) $\tau_{M_1}$ ($\tau_{M_2}$), the torque sensed on motor $M_1$ ($M_2$) in Nm; (2) $\tau_{\theta}$, the sum of no load torques on both motors; and (3) $\theta_{M_1}$ ($\theta_{M_2}$), the absolute angle of motor $M_1$ ($M_2$) in radians. Each condition was obtained empirically. For example, $\mathcal{B}_0$ (Eq. 3) concerns the moment when the center of mass is right above the pivot. At the instant when the event happens, in principle $\tau_{M_1} + \tau_{M_2} = \tau_{\theta}$. But, in practice a small positive margin is needed to make the condition more robust. We chose 0.04 Nm in Eq. 3, which resulted in a local maximum in terms of the experiment success rates. Other conditions were determined in a similar manner and are as follows:

$$\begin{align*}
\mathcal{A}_0 : & \tau_{M_2} > 0.12, \text{ and } \theta_{M_2} = 0 \\
\mathcal{A}_1 : & \tau_{M_2} > 0.12, \text{ and } \theta_{M_2} > 0 \\
\mathcal{B}_0 : & \tau_{M_1} + \tau_{M_2} - \tau_{\theta} < 0.04 \\
\mathcal{B}_1 : & \tau_{M_1} + \tau_{M_2} - \tau_{\theta} > 0.35, \text{ and } \theta_{M_1} < \pi/2 \\
\mathcal{C}_0 : & \tau_{M_2} > 0.085 \\
\mathcal{D}_0 : & \tau_{M_2} < 0.06
\end{align*}$$

Fig. 7 represents two of our experiments done with the direct-drive arm running the state machine in Fig. 6. Due to its reactive nature, the picking operation is performed autonomously with no information on object mass properties and frictional characteristics of the object, fingers, and table top. For planning purposes, the shapes of the objects in Fig. 7 can be projected into a trapezoid and a triangle, respectively. When it comes to executing the resulting manipulation plan, the combination of the semicircular and straight fingers help stabilize the three-dimensional object by suppressing the motions off the plane.

Such experiments were repeated with a range of objects and surface conditions. See Table I. In total, 165 out of 210 trials (78%) were successful. Recall that objects are allowed to slide on the ground and on the end-effector (recall the discussion in Sec. IV-C). To check the effect of the sliding on stable picking, we changed the distance between the pivot of tipping in Sec. IV-C). To check the effect of the sliding on stable picking, we changed the distance between the pivot of tipping and the motor axis from 5 to 35mm for object #7. Here 27 out of 30 trials (90%) were successful. In unsuccessful trials, the robot made a wrong estimate of the position of the CoM in case of reversal the picking motion in a quasistatic manner. See Fig. 9(c). We also tested object picking and placing using a conventional manipulator, Rethink Robotics’ Sawyer arm (Fig. 9(a)). The robot has a parallel-jaw gripper (Fig. 9(b)) equipped on the wrist of a 7 DOF arm. For the experiments here, the robot’s parallel-jaw gripper is not actuated. Our 3D printed, curved finger can be used with the default, straight finger when handling curved objects (Fig. 9(c)).

Given an object of interest, we obtain the gripper trajectory for picking using our direct-drive arm and the Sawyer robot is then position controlled to follow the trajectory in a feedforward, open-loop manner due to its lack of torque sensing capability. Object placing is done in a similar manner, with the placing trajectory prescribed by again our direct-drive arm. We performed a set of experiments with six different objects and the overall success rate was 73% (see Table I). Initial positioning errors and external disturbances (such as the vibration of the manipulator) may account for the unsuccessful trials. Fig. 10 presents picking and placing experiments with the cone-shaped object.

### C. Experiments with a Conventional Manipulator

We also tested object picking and placing using a conventional manipulator, Rethink Robotics’ Sawyer arm (Fig. 9(a)). The robot has a parallel-jaw gripper (Fig. 9(b)) equipped on the wrist of a 7 DOF arm. For the experiments here, the robot’s parallel-jaw gripper is not actuated. Our 3D printed, curved finger can be used with the default, straight finger when handling curved objects (Fig. 9(c)).

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### VI. Conclusion

We presented a robotic in-hand manipulation technique for picking and placing objects that takes advantage of two non-antipodal contacts at fixed distance and gravity. Our manipulation technique can be applied to a wide range of objects and robot platforms and is less dependent on exact contact positioning and sufficiently large internal forces. Experiments with a custom-made autonomous manipulator and a conventional manipulator had high success rates for picking and placing several objects on different surface conditions.

While in principle this approach can work on a large variety of object shapes, rigorously determining the space of all object geometries that will practically work (such as those elongated shapes addressed in our experiments) is left for future work. We are planning to generalize our technique with additional sensing modalities, more dexterous in-hand manipulation skills, and more expressive contact models.

### References


Fig. 7. Two picking experiments with the beverage container (upper) and the cone-shaped object (lower). In (a), the two fingers (one curved, one straight) are in contact with the objects at the instant guard condition $A_0$ (Eq. 1) is satisfied. The instant is marked with the red arrow in (b) where $M_2$ angle is increasing with time. In (c), the CoM is right above the pivot at the instant guard condition $B_0$ (Eq. 3) is satisfied. The instant is marked with the red arrow in (d) where $M_1$ angle is increasing with time. (e) show the configurations after regrasping at the instant guard condition $C_0$ (Eq. 5) is satisfied. The instant is marked with the red arrow in (f) where $M_2$ angle is decreasing with time. After further rotation (g), the objects are lifted up (h).

Fig. 8. Finite state machine for object placing.

Fig. 9. (a) Rethink Robotics’s Sawyer. (b) Original end-effector. (c) Adapted end-effector with a curved finger.

Fig. 10. Implementation on the Sawyer robot showing (a) object picking (clockwise from the top leftmost panel) and (b) placing (left to right).

Fig. 11. Objects used for the experiments in Table I.
<table>
<thead>
<tr>
<th>Object</th>
<th>Mass (g)</th>
<th>Task</th>
<th>Platform</th>
<th>Surface</th>
<th>Number of Trials</th>
<th>Number of Successes</th>
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**Table I**

**Experimental results for object picking and placing. See Fig. 11 for the objects used here.**


