Robust Ungrasping of High Aspect Ratio Objects through Dexterous Manipulation

Ka Hei Mak, Chung Hee Kim, and Jungwon Seo

Abstract—In this work, we address robotic dexterous ungrasping, the capability of securely transferring a grasped object from the gripper to the robot’s environment, i.e. the inverse of grasping or picking, through dexterous manipulation. The situation of dexterous ungrasping can commonly be found in many occasions such as placing a Go stone or inserting a battery pack, where it is necessary to carefully perform contact-rich interactions for stable ungrasping. Advancing from our recent work that formulated a planning framework for dexterous ungrasping, this study addresses the robustness of the motion control for executing the planned ungrasping operations, through an analysis of possible failure cases and caging conditions. We also address how the guaranteed robustness facilitates the modeling and planning of dexterous ungrasping and guides the arrangement of a gripper system. A series of experiments demonstrate the effectiveness of the resulting hardware and software system in practical ungrasping tasks.

Index Terms—Dexterous Manipulation, Robust/Adaptive Control, Grasping

I. INTRODUCTION

UNGRASPING, i.e. inverse of grasping, tasks such as placing a Go stone or inserting a thin battery pack (Fig. 1) may need a careful arrangement. Neither simply dropping nor throwing seems a reasonable way to place the stone on the board. The classical peg-in-hole insertion is inadequate to address all the unique challenges involved in the battery insertion task (for example, compressing the spring in the battery holder). Instead, we humans would typically leverage in-hand manipulation and interaction with the environment to control the object at hand as needed. The geometry of those relatively thin or slender objects, with a high aspect (width-to-thickness) ratio, accounts for this dexterous ungrasping—ungrasping performed with dexterous manipulation (or in-hand manipulation; see [1] for an introduction). Change of grasp is necessary from a typical initial grasp wherein the faces of the object are pinched by the fingers to a goal configuration where the face is brought into contact with a target surface, without losing hold of the object.

Enabling robots to reliably perform such ungrasping tasks that require advanced dexterity remains a great challenge, which may account for why a human operator was needed to help AlphaGo with the placement of Go stones. In the literature, the classical peg-in-hole insertion (see [2] for a survey) is one instance of ungrasping that has received considerable attention. Recently, a broader treatment of ungrasping is explored (for example, manipulation for bin packing [3]) and learning-based approaches are applied to ungrasping tasks (for example, see [4] and the references therein). However, ungrasping through dexterous manipulation, the topic of the presented study, has received scant attention.

Advancing from our recent work on the planning for dexterous ungrasping [5], this study addresses how the computed plans can be realized through motion control. We verify that the underactuated system of the object, the gripper, and the environment (Fig. 1) can indeed be coordinated as planned robustly to errors and uncertainties. This robustness is confirmed by the theory of robotic caging [6], which addresses how to limit the mobility of an object by arranging obstacles that can be robotic fingers/effectors around the object. A caged object might not be completely immobilized, but some challenging issues in prehensile grasping such as contact modeling can be mitigated by caging. Early approaches to computing the cages of two- or three-fingered grippers are shown in [7], [8]. The idea of squeezing and stretching cages and the algorithms for synthesizing cages around polygonal objects were introduced in [9]. Even in case an object is incompletely caged, external forces may bound the mobility of the object as long as its mechanical energy remains less than a threshold. This idea was formalized as the concept of energy-bounded caging [10].

Leveraging our system designed for the benefits of caging (for example, manipulation by palm), we also demonstrate
the performance of secure and robust dexterous ungrasping through a series of experiments in insertion and placement tasks. Likewise, caging has been applied to robustifying robotic grasping and manipulation for decades. Early examples include error-tolerant planar grasping \cite{11}. The relationship between caging and grasping, cages being a precondition for an equilibrium grasp, was examined in \cite{12}. In \cite{13}, the end-effectors that have curved contact surfaces for caging are active. That is, contact interactions between the bodies in contact—the fingers, the object, and the environmental surface—are active. Examples of dexterous whole-hand manipulation were demonstrated in \cite{14}. Robust cooperative object manipulation was presented in \cite{15}.

**II. Preliminaries and Problem Description**

This section presents a review of our preliminary study and states a problem to be addressed in this work.

**A. Preliminaries**

Our recent studies \cite{5}, \cite{16} address how dexterous manipulation is applicable to ungrasping situations, i.e. dexterous ungrasping, as depicted in Fig. 1. The overall procedure is realized as a motion control task for the robot, planned by Algorithm 1. The algorithm, based on RRT* \cite{17}, searches for a feasible motion path connecting the initial configuration \( q_{\text{init}} \), where an object is pinched-grasped by a gripper, to the goal \( q_{\text{goal}} \), where the object rests on a target surface, in an optimal manner with respect to a certain criterion.

A planned path by Algorithm 1 represents a series of dexterous actions, that is, contact interactions between the bodies in contact—the fingers, the object, and the environmental surface. Constructively, these actions are standardized into a set of motion primitives of contact interaction. Examples of the primitives are illustrated in Fig. 2 with a linear object model handled by a two-fingered gripper on the plane normal to the target surface. The object is in contact with the target surface at the point \( G \) and with the gripper’s digits at the points \( A \) and \( B \). All the bodies in contact are assumed to be rigid. Each primitive is expressed by the specification of the modes of contact: \( R_X \) \( (S_X) \) denotes rolling (sliding) at contact \( X \). Fig. 2 thus shows the primitives \( R_GR_A S_B \), \( R_GR_A R_B \), and \( R_G S_A S_B \). See how the object-gripper-environment system is reconfigured according to the contact modes at \( G \), \( A \), and \( B \).

Our algorithm then exploits the configuration space of the system using the primitives (UngraspPrimitives in line 5, Algorithm 1).

![Fig. 2: Three motion primitives of contact interaction. The bodies in contact are reconfigured through sliding or rolling at the contacts \( G \), \( A \), and \( B \).](image)

To securely keep hold of the object, it is verified whether force-closure \cite{18} can be attained when a new node is added to the search tree \( \mathcal{T} \) (the method Free in line 6). In other words, the free configuration space \( C_{\text{free}} \), i.e. the search space of the algorithm, is defined to be:

\[
C_{\text{free}} = (C \cap C_{\text{grasp}}) \setminus C_{\text{obs}}
\]

where \( C \) is the configuration space of the object-gripper-environment system in which all the contacts \( G \), \( A \), and \( B \) are active. \( C_{\text{obs}} \) is the collection of those configurations where these bodies are in collision, e.g. between the thumb and the ground surface when \( \theta \) is small (Fig. 2). At the configurations in \( C_{\text{grasp}} \), the contact wrenches can attain force-closure.

Fig. 3 instantiates planned dexterous ungrasping motions computed for a coin (with a rectangular side profile) and a Go stone (with a curved profile) using a parallel-finger gripper. Note that digit asymmetry, i.e. difference in digit lengths denoted \( \alpha \) in Fig. 3 is incorporated in the search process. \( \alpha \) plays a key role in successful planning (more details in \cite{5}). Specifically, Algorithm 1 would fail to find a force-closure path using an ordinary gripper whose fingers are the same length (\( \alpha = 0 \)). A feasible value of \( \alpha \) is found by solving for possibly multiple planning queries. The examples also show the efficacy of the planar ungrasping setting (Fig. 2) in the real tasks of coin and Go stone placement.

**B. Problem Description**

The main research question of this presented work is concerned with the realization of the computed plans for dexterous ungrasping by Algorithm 1, such as the ones in Fig. 3 that...
below, we discover two general cases exclusive to each other by examining how the feasible twist polytope evolves throughout the entire process of ungrasping, for a linear object in a planar setting (to be generalized in Sec. III-B).

**Lemma 1.** At almost all the grasps of the three contacts $G$, $A$, and $B$ where $0^\circ < \theta, \psi < 90^\circ$ (Fig. 2), a linear object can escape from the grasp without violating the first-order contact constraints either proximally toward the base of the gripper, through the gap between $A$ and $B$, or distally away from the base, through the gap between $A$ and $G$, but not both ways allowed simultaneously.

**Proof.** Fig. 4 shows three configurations of the system, each of which is marked on the $\theta \psi$-plane and is overlaid with the object’s feasible twist polytope, the red-shaded area, as the region of its allowable centers of rotation according to Reuleaux’s method [2]. The object is allowed to move, without penetrating the gripper or the environment, by instantaneously rotating about a point in that region. The + or − label denotes the direction of rotation: + counterclockwise and − clockwise. The specific location of the center of rotation also encodes information about possible contact modes: in the interior of the region, all the contacts $G, A$, and $B$ are breaking; on the edges, one contact remains active; and at the vertices, two contacts active. The three distinct cases shown, with a single triangular region labeled $+/−$ or all the three normals intersecting, are exhaustive, considering the relative orientation between the normals: the normal at $A$ is always steeper than the normals at $B$ and $G$ with respect to the face of the linear object.

- First, in the case of Fig. 4(a), the mobility analysis dictates that it is impossible for the object to escape from the grasp distally through the gap between $A$ and $G$. In other words, loss of grasp can occur only by the object’s moving proximally toward the base of the gripper through a counterclockwise rotation about one of the allowed...
Second, in the case of Fig. 4(b), it is impossible for the object to escape proximally through the gap between A and B. Loss of grasp can occur only by the object’s moving distally through a clockwise rotation about one of the allowed centers.

Lastly, in the case of Fig. 4(c), the three contact normals have a common intersection. The object is thus allowed to rotate about it in either direction instantaneously. The collection of the configurations where this bidirectional instantaneous rotation is allowed forms a lower-dimensional subspace, named dual-mobility manifold in Fig. 4 because of the equality constraints on the intersecting contact normals.

Therefore, at almost all the configurations except the measure-zero set of the dual-mobility manifold, either the case of Fig. 4(a) or Fig. 4(b) happens, but not both cases allowed simultaneously.

Although the object can be deviated from the planned path as discovered in Lemma 1, it is possible to immobilize the object by simply adding one unit contact wrench:

**Lemma 2.** At almost all the grasps of the three contacts G, A, and B described in Fig. 2(a-b), adding one unit contact wrench can make the linear object immobile to the first order.

**Proof.** This is constructively verified as follows. First, in the case of Fig. 4(a), suppose that we add a unit wrench that is tangential to the thumb’s face at B and pointing toward the thumb’s tip. By doing so, the allowed twists are not feasible any more because the reciprocal product of any allowed twist and the additional unit wrench is always negative and the two screws are then contrary. The object is then immobile to first order or in first-order form-closure. Second, in the case of Fig. 4(b), an additional unit wrench tangential to the support surface at G and pointing to the right is contrary to the allowed twists. □

Lemmas 1 and 2 disclose that the object is geometrically in a narrow corridor with a dead end, i.e. in a concave hole, at almost all the configurations in its free space. This makes it easier to cage the object, as formalized below.

**Lemma 3.** The linear object in almost all the three-contact grasps described in Fig. 2(a-b) is in an energy-bounded cage; more specifically, an energy potential can be defined such that a positive amount of work is needed to take the object arbitrarily far away from the gripper.

Proof. We present a constructive proof by referring to Fig. 5 that reproduce the grasps in Fig. 3(a-b) in a conservative setting ignoring the finger’s geometry. Fig. 5 also features potential fields $U$ that induce forces aligned with the additional unit wrenches in Lemma 2. First, in Fig. 5(a), the distal end of the object (currently at $G$) needs to reach $A$ in order for the object to escape from the grasp since it is impossible for the object to pass through the space between $G$ and $A$. This requires a work done against the potential whose equipotential lines are normal to the linear thumb, in case $0^\circ < \theta, \psi < 90^\circ$ as assumed in Lemma 1. Second, for the object to escape in Fig. 5(b), the proximal end of the object (currently at $B$) needs to reach the tip of the thumb. This also requires a positive work against the potential set normal to the ground surface. □

We now provide examples of the energy potentials for energy-bounded caging applied in Lemma 3. As addressed in the lemma, a legitimate energy potential $U(p, p_0)$, the energy required to move the object from a reference configuration $p_0$ to another $p$, needs to be based on the additionally required unit wrench used in the proof of Lemma 2. First, in the case of Fig. 4(a), the gravitational potential energy

$$U(p, p_0) = mg(z - z_0)$$

(2)

based on gravity acting downward on the page, where $z$ denotes the height of the center of mass of the object, is a suitable energy potential. Second, in the case of Fig. 4(b), the work to be done against the friction at $G$

$$U(p, p_0) = -\int_{p_0}^p f_G \cdot dx$$

(3)

where $f_G$ denotes the contact force at $G$ and $x$ is the trajectory of $G$ on the support surface from $p_0$ to $p$, works for caging. In addition, it is possible to set up an energy potential in a more proactive manner by taking advantage of configuration-dependent sliding motion. This is depicted in Fig. 6 with the motion primitives $S_G R_A S_B$ and $S_G R_A R_2$ in which $G$ is slid to the right (left) in Fig. 6(a) (Fig. 6(b)) when the present mobility of the object corresponds to the case of Fig. 4(a) (Fig. 4(b)). Sliding $G$ will maximize the friction at $G$ along
the edge of the friction cone. Furthermore, if the sliding motion is performed dynamically, the inertial force will additionally increase the minimum energy required to escape the cage. If $G$ were fixed, these primitives would be the same as $RGR_A S_B$ and $RCR_A R_B$ in Fig. 2. Therefore, they are readily realized by superposing a translational motion for the gripper along the support surface onto the primitives in Fig. 2 and can then be used in Algorithm 1.

We finally remark on the conservativeness of the presented analysis based on the first-order geometry. In practice, higher-order effects will further contribute to constraining the object. For example, the object at the configuration of Fig. 4(c), on the dual-mobility manifold, would be completely immobilized if the radius of curvature of the fingertip were sufficiently large.

**B. Robust Motion Control for Dexterous Ungrasping**

Given linear object shapes, we now answer the question about the viability and robustness of motion control for our ungrasping manipulation (Sec. II-B) affirmatively based on the fact that the object being ungrasped is caged in terms of both geometry and energy. The active, motion-controlled gripper and the passive, underactuated object will stay in contact (or nearby) unless the minimum energy required to escape the cage is exceeded by disturbances, as the gripper is controlled to execute a planned motion. Possible loss of contact due to the errors in positioning may break force-closure; still, the object can remain caged.

In what follows, we further discuss how the special-case robustness established with a linear object model can be exploited to handle more complex object shapes and to facilitate planning. Our experiments will show how these conceptual benefits matter in practice.

1) **Simplified Object Model:** The subset property of cages [10] suggests that the cages identified with the linear object model, as examined in Sec. III-A, work for any actual object shapes “grown” from the simple geometry. In Fig. 4(b) for example, any other planar shapes containing the line segment object shape cannot escape from the cage toward the base of the gripper. This benefit of using an undersized model to caging justifies the use of simplified models in the planning (Algorithm 1). The undersized model will also contribute to increasing the internal forces of the force-closure grasps resulting from the planning, by means of passive compliance. We therefore suggest a practical way to cope with a possibly complex, nonlinear object profile: execute an ungrasping motion planned with a simple, standardized line segment or rectangular model, rather than with exact geometry, in an open-loop manner without feedback while depending on the robustness. A limitation of this approach is that size underestimation due to conservative modeling may result in more forceful interaction between the gripper and the object.

2) **Planning with Enlarged Free Space:** If the energy expenditure required to escape the cage is considered to be sufficiently large, it becomes unnecessary to limit $C_{\text{grasp}}$ in Algorithm 1 to force-closure grasps because the object will be held essentially stable no matter whether the object is in force-closure or not. This relaxation of $C_{\text{grasp}}$ will enlarge the free space $C_{\text{free}}$, and reduce the running time of the algorithm. For example, see Fig. 7(a) showing our finger-thumb gripper model with a palm, another rigid contact surface situated between the finger and the thumb. The contact $B$ is now formed at the concave vertex between the thumb and the palm, and this will suppress one of the two failure modes: the object escaping proximally toward the base of the gripper. The use of the palm thus makes it unnecessary to test force-closure at the configurations like Fig. 4(a), which can be identified by running a linear program for Reuleaux’s method whose problem size is smaller than the force-closure test. In Fig. 4(b), both $B$ and $G$ are at a concave vertex in the situation of insertion with a palm. The figure also shows the cones of the frictionless contact wrenches at $G$ and $B$, each of which is spanned by the two contact normals, denoted $w_{X_1}$ at the concave vertex. If $G$ and $B$ can “see each other” inside both cones, then form-closure [18] is attained: the object is completely immobilized. With right angle corners at $G$ and $B$ as illustrated in Fig. 7(b), the object is in form-closure at any $(\theta, \psi)$ where $0^\circ < \theta, \psi < 90^\circ$.

**IV. EXPERIMENTS**

This section introduces our system for robust dexterous ungrasping and presents a series of experiments. See also the video attachment.

**A. Hardware and Software**

Fig. 8(a) shows our customized parallel-finger gripper incorporating digit asymmetry (the finger longer than the thumb) for feasible planning (Fig. 3) and an extendable palm device for palm-assisted ungrasping (Sec. III-B). The palm end-effector is driven by the Sarrus linkage (Fig. 8(b)), a one-DOF six-bar parallel linkage that generates a linear motion for the end-effector along the slit in the fingers. The top platform carries the end-effector and the bottom one is docked on the base gripper. The workplanes of the legs are arranged not to interfere with the base gripper. The palm prototype is actuated by one servo motor through a gear train; overall, these weigh 240g and the maximum pushing force that the palm effector can exert is 4.9N. Fig. 8(c) shows our experiment setting.

Our control software for dexterous ungrasping is organized as a ROS package. It coordinates the low-level drivers of the palm’s servo motor, the two-fingered gripper, and a UR10 manipulator arm carrying the gripper, and executes an ungrasping motion generated by our planner.

Visit our GitHub page [link](https://github.com/HKUST-RML/dexterous_ungrasping.git)
configuration, 30 times for each of the four different holder orientations in an open-loop manner from the corresponding feasible initial configuration, 30 times for each of the four different holder orientations. The causes of the failure include the spring forces, which resulted in the battery’s escaping toward the base of the gripper. Since the configuration where the spring is compressed, $q_{\text{goal}}$, is quite close to the dual-mobility manifold (see Fig. 9(a)), the desired mobility shown in Fig. 4(b) is not guaranteed robustly. In our previous work [16], the success rate of battery insertion without the palm device was 18/20 using an ordinary parallel-finger gripper ($\alpha = 0$), which made it possible to robustly get to the cage configuration like Fig. 4(b) with sufficiently large $\psi$. However, with the gripper of zero $\alpha$, it took a longer time to complete insertion because the terminal value of $\psi$ needs to be $90^\circ$. Our palm device successfully compensates for the disadvantage of increased $\alpha$ while retaining its advantage in reduced duration, with the high success rate.

### B. Robust Insertion

We first tested our robust ungrasping in the task of dry battery insertion: assemble a cylindrical AA battery with a spring-loaded holder. This is more complex than other insertion tasks in that it is necessary to push the battery forward to compress the spring in the holder. If the spring compression is done at a cage configuration like Fig. 4(a), where it is possible for the object to escape toward the base of the gripper, the spring force can cause loss of grasp.

With the palm device, an object will remain caged all the time (Fig. 7(b)). The planning for the ungrasping was thus performed without testing force-closure. Fig. 9(a) shows a path planned with the two motion primitives $R_G R_A S_B$ and $R_G R_A R_B$ when the amount of finger asymmetry $\alpha = 0.3$, which in turn set the terminal value of $\psi$ around $40^\circ$. At $q_{\text{goal}}$, on the boundary of $C_{\text{obs}}$, the push-down maneuver in Fig. 9(b) was performed to terminate insertion without lowering the thumb because the $R_G R_A R_B$ primitive would cause the collision between the thumb and the hole. The event of spring compression happens at $q_{\text{goal}}$ before the push-down, by translating the gripper parallel to the hole’s bottom face.

After the gripper picked up a battery from a stand (Fig. 8(c)) and brought it to the holder, the planned motion was executed in an open-loop manner from the corresponding feasible initial configuration, 30 times for each of the four different holder orientations, $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ (Fig. 9(c)). The overall success rate was 119/120 with an average cycle time of 11.1 seconds per attempt. The only unsuccessful event occurred at the orientation $270^\circ$, where the battery escaped from the gripper sideways. We also performed insertion with the arm and the gripper operating at their maximum possible speed, at the holder orientation $0^\circ$. No failures were witnessed out of 30 trials and the total cycle time was around 4.3 seconds for each trial.

Without the palm device, the planner was unable to find a solution when $\alpha = 0.3$, as can be inferred from the shape of $C_{\text{free}}$ with no palm in Fig. 9(a). When the previously planned motion was executed anyway without the palm for comparison, no successful outcomes were witnessed at any of the four holder orientations. The causes of the failure include the spring forces, which resulted in the battery’s escaping toward the base of the gripper. Since the configuration where the spring is compressed, $q_{\text{goal}}$, is quite close to the dual-mobility manifold (see Fig. 9(a)), the desired mobility shown in Fig. 4(b) is not guaranteed robustly. In our previous work [16], the success rate of battery insertion without the palm device was 18/20 using an ordinary parallel-finger gripper ($\alpha = 0$), which made it possible to robustly get to the cage configuration like Fig. 4(b) with sufficiently large $\psi$. However, with the gripper of zero $\alpha$, it took a longer time to complete insertion because the terminal value of $\psi$ needs to be $90^\circ$. Our palm device successfully compensates for the disadvantage of increased $\alpha$ while retaining its advantage in reduced duration, with the high success rate.

### C. Robust Precision Placement

Next, we test precision placement: place an object at a specific location on a tabletop securely all the way from an initial pinch grasp, similarly to the previous insertion experiments but on a flat surface. The objects we tested are a coin, a hardcover book, a playing card, a 3D-printed rectangular plate, and a Go stone. The following paragraphs report a range of scenarios to test robustness.

1) Placement through Cages: We tested the performance of precision placement on a level surface with two types of motion paths: (1) a nominal force-closure path and (2) a path with no force-closure initially but energy-bounded-caged under the influence of gravity (recall the discussion around Eq. 2). Fig. 3(a) shows these two paths, one from $q_{\text{init}}$ and the other from $q'_{\text{init}}$, for the coin. The two ungrasping operations for the coin, also similarly for the hardcover book and the playing card, were performed as shown in Fig. 10(a). An attempt of placement is regarded as a success if no loss of grasp occurs until the final push-down maneuver (Fig. 9(b)) is performed at a small value of $\theta$ to terminate the ungrasp. The overall success rate with the caged paths was 110/120 = 91.7% (Table I), commensurate with 88.3% [5], the success rate with the force-closure paths. Also reported in the table are placement errors, i.e. the precision of placement. Fig. 10(b) shows the progress of ungrasping with the 3D-printed plate when the motion primitive $R_G S_A S_B$ was applied. In palm-assisted ungrasping shown on the right, no failures happened in 40 trials with the average placement error of 0.8mm (3.1mm with no palm [5]).
of the coin as suggested in Sec. III-B. In these experiments, been customized with exact geometry as shown in Fig. 3(b). The plan for the Go stone could have success rate of 38/40. The plan for the Go stone was mostly held securely, with a (Fig. 3(a)), which is thinner than the Go stone (the diameters are similar). The Go stone was mostly held securely, with a placement (Fig. 1) was performed with the same ungrasping done with no size underestimation. Likewise, the Go stone experiments was 39/40, higher than the previous experiments and increased internal forces. The success rate of the new benefits of an undersized object model (Sec. III-B): caging redid placement. The goal of this experiment is to exploit the angles formed by the battery holder and the horizontal are 0◦, 90◦, 180◦, and 270◦, respectively.

The hard-cover book was apparently the most challenging object in terms of the success rates of the experiments presented above (Table I). We deliberately underestimated the size of the book (4mm thinner than actual), planned a new ungrasping path, and redid placement. The goal of this experiment is to exploit the benefits of an undersized object model (Sec. III-B): caging and increased internal forces. The success rate of the new experiments was 39/40, higher than the previous experiments done with no size underestimation. Likewise, the Go stone placement (Fig. 1) was performed with the same ungrasping path and the same finger combination planned for the coin (Fig. 3(a)), which is thinner than the Go stone (the diameters are similar). The Go stone was mostly held securely, with a success rate of 38/40. The plan for the Go stone could have been customized with exact geometry as shown in Fig. 3(b). Instead, we take advantage of the simpler, rectangular profile of the coin as suggested in Sec. III-B. In these experiments, however, placement errors worsened. This may be accounted for by more forceful interactions between the gripper and the object caused by size underestimation.

2) Placement with Undersized Object Model: The hardcover book was apparently the most challenging object in terms of the success rates of the experiments presented above (Table I). We deliberately underestimated the size of the book (4mm thinner than actual), planned a new ungrasping path, and redid placement. The goal of this experiment is to exploit the benefits of an undersized object model (Sec. III-B): caging and increased internal forces. The success rate of the new experiments was 39/40, higher than the previous experiments done with no size underestimation. Likewise, the Go stone placement (Fig. 1) was performed with the same ungrasping path and the same finger combination planned for the coin (Fig. 3(a)), which is thinner than the Go stone (the diameters are similar). The Go stone was mostly held securely, with a success rate of 38/40. The plan for the Go stone could have been customized with exact geometry as shown in Fig. 3(b). Instead, we take advantage of the simpler, rectangular profile of the coin as suggested in Sec. III-B. In these experiments, however, placement errors worsened. This may be accounted for by more forceful interactions between the gripper and the object caused by size underestimation.

3) Placement with Configuration-Dependent Sliding: We repeated the challenging placement of the hardcover book with perturbed paths in which the gripper can be randomly dislocated by up to 5mm from its nominal position along the force-closure path used in Fig. 10(a). Not surprisingly, the success rate dropped to 23/40. Next, we applied configuration-dependent sliding (Fig. 6) to enhance robustness, considering the switch of mobility across the dual-mobility manifold. Fig. 10(c) shows the resulting maneuver: the robot slides the object first to the left with S2CRA3SB and then to the right with S3CRA2RB. This resulted in an improved success rate of 32/40, despite the intentional 5mm errors. Without the errors, the success rate was higher with 38/40.

### Table I: Experiment results of precision placement.

<table>
<thead>
<tr>
<th>Section Reference</th>
<th>Task Object</th>
<th>Object Dimension ( l_{\text{obj}} \times \text{thickness} ) (mm)</th>
<th>Digit Asymmetry</th>
<th>Initial Configuration ( \alpha )</th>
<th>Placement Error Mean ( \ell_{\text{goal}} ) (mm)</th>
<th>Placement Error Range ( \ell_{\text{goal}} ) (mm)</th>
<th>Success Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV-C1</td>
<td>Coin</td>
<td>27 × 3</td>
<td>0.30</td>
<td>0.75</td>
<td>75</td>
<td>−1.5</td>
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<td>0.65</td>
<td>75</td>
<td>−0.2</td>
<td>[−3, 2]</td>
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<td>0.63</td>
<td>70</td>
<td>−2.5</td>
<td>[−4, 1]</td>
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<tr>
<td>IV-C1</td>
<td>3D-printed plate(^1)</td>
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<td>0.65</td>
<td>25</td>
<td>1.3</td>
<td>[−4, 4]</td>
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<td>IV-C2</td>
<td>Hardcover book(^2,3)</td>
<td>160 × 25</td>
<td>0.47</td>
<td>0.65</td>
<td>25</td>
<td>−1.8</td>
<td>[−12, 6]</td>
</tr>
<tr>
<td>IV-C2</td>
<td>Hardcover book(^3)</td>
<td>160 × 25</td>
<td>0.47</td>
<td>0.65</td>
<td>25</td>
<td>−0.4</td>
<td>[−3, 4]</td>
</tr>
</tbody>
</table>

\(^1\) Extendable palm device applied. \(^2\) Gripper dislocated from its nominal motion path. \(^3\) Placement with configuration-dependent sliding.
from $q$ with the primitives $S$ and completing autonomous and dexterous pick-and-place. In this study, we have addressed that during the course of dexterous ungrasping the object can be retained stably by the cage formed by the robot and the environment. This facilitates the way to model, plan, and execute dexterous ungrasping operations through motion control. Our experiments show the robustness of the cage-based, motion-controlled dexterous ungrasping to external disturbances and the effectiveness of the featured design principles, i.e. digit asymmetry and palm-ungrasping to external disturbances and the effectiveness of robustness of the caging-based, motion-controlled dexterous operations through motion control. Our experiments show the way to model, plan, and execute dexterous ungrasping cage formed by the robot and the environment. This facilitates and a playing card. (b) Progress of placement through the motion primitive $R_G S_A S_B$ without (left) and with palm (right). (c) Configuration-dependent sliding with the primitives $S_C R_A S_B$ and $S_G R_A R_B$ applied to hardcover book placement.

V. CONCLUSION

In this study, we have addressed that during the course of dexterous manipulation and robust grasping: a difficult road toward simplicity,” IEEE Trans. Robot. Automat., vol. 16, no. 6, pp. 652–662, 2000.


REFERENCES


