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High-Speed Scooping: An Implementation through Stiffness Control and Direct-Drive Actuation

Ka Hei Mak, Pu Xu, and Jungwon Seo

Abstract— **This study presents the technique of robotic high-speed scooping: rapidly picking an object lying on a support surface by making contact with the object's open top face and the bottom face that is hidden in contact with the support surface. Essential to high-speed scooping is thus to make suitable dynamic, impactful interaction happen among the robot, object, and environment under errors and uncertainties. We propose a solution to this challenge based on stiffness control, an approach for indirect force control using the robot that is arranged to behave like a desired mechanical system. An implementation of the solution is then presented using a custom-built two-fingered direct-drive gripper. Our experiments verify that high-speed scooping operation is achievable, with the duration of dynamic interaction less than 0.3 s, and effective to various scooping situations featuring objects durable and fragile.**

I. Introduction

The capability of picking/grasping various objects sounds trivial to people, but it is still quite difficult to make happen with the robots at present. A wide variety of exceptions and corner cases, outside the range of conventional robotic manipulation solutions, are prevalent in the tasks of object picking/grasping. One example is the situation in which an object to pick, with a possibly flat bottom face, is in contact with a hard support surface. The thinner the object is, the more challenging the task becomes. For example, picking a thin plastic card off from a tabletop could be quite tricky to people sometimes. Suctioning may work, but it cannot solve all the problems. For multi-fingered grippers, the practice of *scooping* has been around as a viable solution to the situation, in which one digit is managed to penetrate underneath the object while another puts pressure on it.

In this study, we present the technique of *high-speed scooping* manipulation based on stiffness control that is suitable for rapidly scooping an object using a multi-fingered gripper, a departure from the use of suction cups on a motion-controlled robot platform and also other existing solutions. Fig. 1 shows the time-lapse sequence of our high-speed scooping performed by our custom-built two-fingered direct-drive gripper. The motion-controlled arm begins the operation of high-speed scooping by "slamming" the gripper onto a hard supporting surface. The gripper then senses a collision with the surface and reacts by executing the operation of scooping—cramming one digit into the small space between the object and the surface while the other digit is kept pushing down on the object. In the meantime, it is unnecessary to completely stop the arm's motion even for a very small amount of time and all these interactions can be performed successfully in around 0.3 s.

Corresponding to Jungwon Seo (junseo@pusan.ac.kr), Pusan National University, Rep. of Korea.

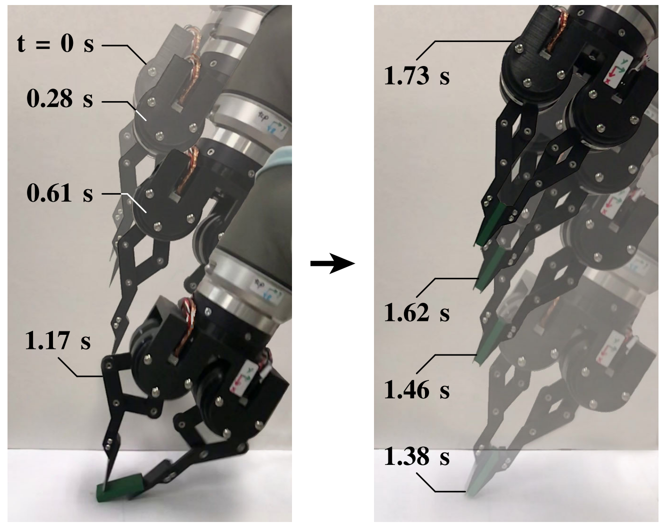

Fig. 1. Our high-speed scooping performed by a direct-drive gripper, for picking a domino block off from a hard surface. The arm can practically slam the gripper onto the surface while the object is being scooped.

This paper is organized as follows. After reviewing related literature in Sec. II, we provide the strategy for high-speed scooping in Sec. III. Sec. IV presents our implementation of high-speed scooping along with a set of experiments done with various objects both durable (for example, the domino block in Fig. 1) and fragile (for example, snack items like nacho chips).

II. Related Work

There are a wide range of approaches for enabling robots to pick/grasp objects in a way adaptive to the environment, such as in the scooping situations. One notable approach is to take advantage of passive compliance and the resulting underactuation provided by soft materials or compliant mechanisms [1]–[4]. Active contact interactions by means of added gripper components such as rollers or belts also prove effective [5], [6]. Our research group has also been devising relevant techniques for picking/grasping [7]–[9], placing/ungrasping [10]–[12], and mobile manipulation tasks [13], [14].

Our high-speed scooping technique to be presented in this paper builds on impedance/stiffness control, also called indirect force control. A robot executing impedance/stiffness control is arranged to behave like a customized mechanical

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system such as a mass-spring-damper system that reacts to external forces as desired. Early pioneering works in the control scheme can be seen in [15], [16]. Notable applications showing its usefulness in robotic manipulation involving physical environmental interactions include the classical passive/active remote-centered compliance [17], [18] and recent works in impedance controllers for robots with passive flexible joints [19], [20].

Our high-speed scooping manipulation is implemented through the use of direct-drive actuation [21] with no high reduction ratio transmission. Its advantages have been known for decades but were difficult to realize in manipulation tasks due to, for example, the unavailability of suitable actuators. Examples of direct-drive robotic grippers can be found in [22], [23]. In robotic locomotion, with possibly less stringent limitations on space than manipulation, direct-drive actuation proves suitable for adaptive multi-modal gaiting [24]. Proprioception provided by direct-drive actuation also facilitates sensing in physical contact situations [25], [26]. Quasi-direct-drive actuation [27] is a way to mitigate the downsides of direct drive.

III. Strategy for High-Speed Scooping

In this section, we state the research question in this work and discuss our strategy for high-speed scooping.

A. Problem Description

The research question posed in this presented study is concerned with how to perform the manipulation of scooping over a wide range of objects at high speed, termed as *high-speed scooping*. This is a departure from existing solutions to robotic scooping through underactuation, with a limited ability to actively adapt to various situations, or motion control, with dependence on the availability of accurate geometric information. Critical to high-speed scooping are the capabilities for rapidly responding to contact interactions between the object, robot, and environment under errors and uncertainties regarding the geometry, configuration, and physical properties of the bodies that physically interact.

B. High-Speed Scooping through Stiffness Control

One viable approach to address the challenges of high-speed scooping is to arrange for the robot to behave like the mechanical system that interacts with the object and environment as desired, according to the formalism of impedance control [16]. Specifically, in this presented study the robot is abstracted as a finger-thumb pair (see the point finger and the flat-faced rigid thumb in Fig. 2) and each of the digits, assumed to move freely, is controlled to render a passive mass-spring-damper system according to stiffness control [15], a specialized form of impedance control:

$$m_{\mathrm{f}}\ddot{\mathbf{p}}_{\mathrm{f}} + b_{\mathrm{f}}\dot{\mathbf{p}}_{\mathrm{f}} + k_{\mathrm{f}}(\mathbf{p}_{\mathrm{f}} - \mathbf{p}_{\mathrm{f}}^{d}) = \mathbf{f}_{\mathrm{f}} \quad (1)$$

$$m_{\mathrm{t}}\ddot{\mathbf{p}}_{\mathrm{t}} + b_{\mathrm{t}}\dot{\mathbf{p}}_{\mathrm{t}} + k_{\mathrm{t}}(\mathbf{p}_{\mathrm{t}} - \mathbf{p}_{\mathrm{t}}^{d}) = \mathbf{f}_{\mathrm{t}} \quad (2)$$

Eq. (1) above represents the second-order mass-spring-damper dynamics on target for the finger (the subscript 'f'); Eq. (2) is for the thumb (the subscript 't'). m, b, k, and

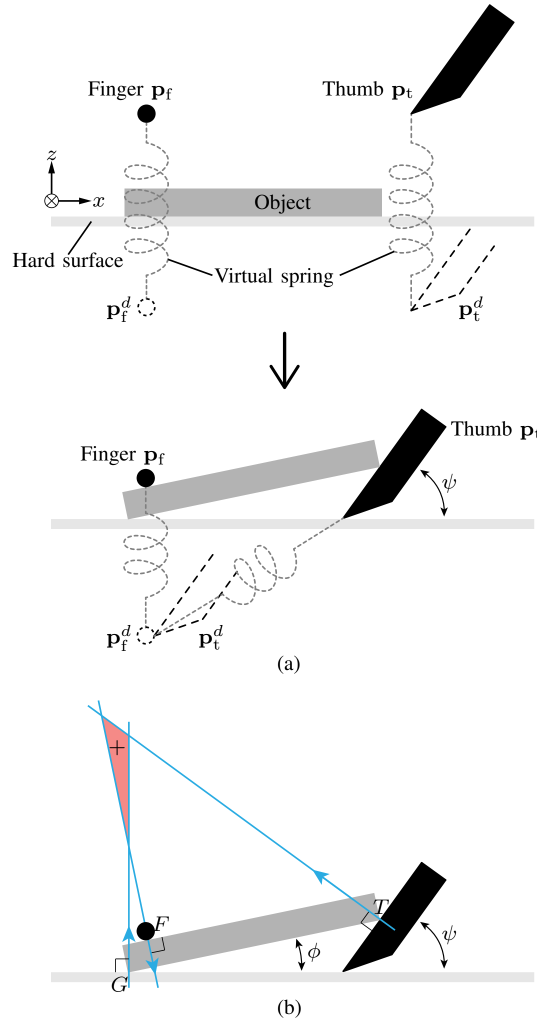


Fig. 2. (a) Two-step procedure for scooping through stiffness control. All the bodies (finger, thumb, object, and surface) are assumed to be rigid. (b) Scoopability analysis following [9]. Due to the contact constraints shown as the contact normals at the points F (finger-object), T (thumb-object), and G (ground-object), the object is kinematically unable to escape through the gap between F and G. In other words, the object at the configuration is only allowed to instantaneously rotate about a point in the region shaded red, counterclockwise (encoded by the "+" sign).

$\mathbf{f}$ denote the mass, damping constant, spring constant, and external force. $\mathbf{p} = [x \ z]^T$ and $\mathbf{p}^d = [x^d \ z^d]^T$ represent the actual and the desired position, respectively. $\mathbf{p}^d$ is also interpreted as the rest position of the virtual spring according to the dynamics in Eq. (1-2).

Concretely, we then consider how to move the set points of the virtual springs, i.e. the rest position $\mathbf{p}^d$, in order to achieve desired contact interactions. Fig. 2(a) depicts our two-step procedure. First, in the top panel of Fig. 2(a), $\mathbf{p}_{\mathrm{f}}^{d}$ and $\mathbf{p}_{\mathrm{t}}^{d}$ are set to be located below the support surface. This will bring the finger (thumb) into contact with the object (surface). Second, in the bottom panel of Fig. 2(a), $\mathbf{p}_{\mathrm{t}}^{d}$ is set such that the thumb's tip coincides with $\mathbf{p}_{\mathrm{f}}^{d}$, which is kept fixed, after the gripper makes contact with the environment in the previous step. This will cause the gripper to close and thus to pinch the object.

To justify the strategy for high-speed scooping stated so far, it is necessary to consider how it is possible for the thumb to initially get through between the surface and the object. We hypothesize that if the thumb is harder than the object and approaches to the object with a sufficiently small angle of attack ψ, the initial penetration is achievable. This point was also addressed in our recent study [9] along with experiments. In terms of stiffness control, $k_{\mathrm{f,t}}$ may need to be set sufficiently large such that the thumb moves with sufficiently large kinetic energy and the finger presses down on the object with a sufficiently large force. Another issue to consider is how to bring the object into a final pinch grasp without losing it. We place the finger $\mathbf{p}_{\mathrm{f}}$ on the object such that the object is *scoopable* (see again our work [9]). A mobility analysis (Fig. 2(b)) then confirms that the object cannot escape from the grasp through the gap between the finger and the ground, if the finger and thumb are fixed, and thus the object will comply with the gripper's closing motion.

Our approach for high-speed scooping offers clear advantages. No exact information on the height of the surface or the location of the object is necessary because of the passive imposed dynamics (Eq. (1-2)) and the robustness of scoopability [9] (that is, in Fig. 2(b), scoopability is valid as long as the triangular region shaded red does not vanish). Compared to rigid motion control or underactuated control, the contact forces between the bodies interacting can be mitigated by, for example, actively adjusting $k_{\mathrm{f,t}}$.

IV. Practice of High-Speed Scooping

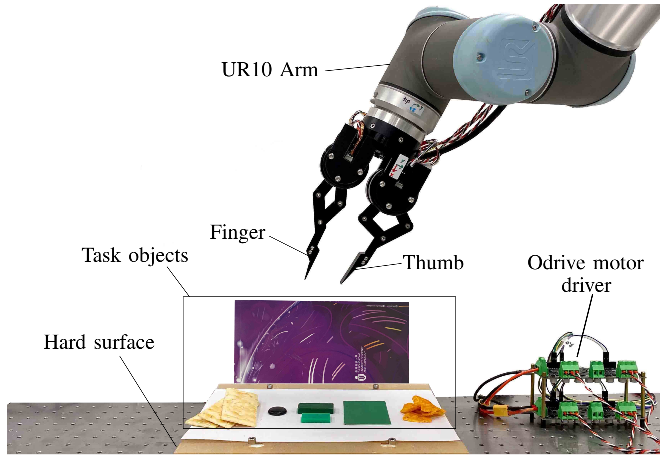
This section presents the implementation of high-speed scooping along with a set of experiments.

A. System Setting

Our overall hardware setting is shown in Fig. 3(a). A motion-controlled UR10 arm carries our two-fingered custom-built gripper that has four degrees-of-freedom (DOF) and adopts direct-drive actuation.

Fig. 3(b) presents a close-up of our gripper. Overall, the gripper is inspired by the study presented in [23]. Each two-DOF finger is constructed from a symmetric five-bar linkage that is actuated by two T-Motor GB54-2 BLDC motors with no gear train. ODrives and AS5048A hall-effect encoders are used for controlling the motors and providing position feedback, respectively. Our website[1] has more details of how we engineered the gripper. Our driver software[2] that provides a user interface to the gripper hardware is also available. Using the gripper with direct-drive actuation, we implement the stiffness control task in Eq. (1-2) as proportional-derivative (PD) motion control. The necessity of gravity compensation is minimal in our setting since the heavy motors of the gripper are carried by the motion-controlled arm and the five-bar digit linkages are lightweight (25 g for each digit). This makes it possible to set the controller's P-/D-gains quite small and thus realize suitably compliant responses.

[1][Online] `https://github.com/HKUST-RML/ddh_hardware`
[2][Online] `https://github.com/HKUST-RML/ddh_driver`



(a)

(b)

Fig. 3. (a) Experiment setting. (b) Our custom two-fingered direct-drive gripper.

B. Experiments

The timeline of the implemented process of our high-speed scooping is instanced in Fig. 4. The details are as follows[3]:

1) *Initial Approach* (before time $t = 1.12$ s): First, the gripper carried by the arm is positioned above the object and configured such that a desired angle of attack ψ is formed between the thumb's face and the ground surface. The gripper is then slammed on the surface, whose height does not need to be known a priori, as fast as around 0.45 m/s.
2) *Interact with Environment* ($t = 1.12$ s): The collision between the gripper's digits and the object/surface is detected by measuring the displacement of the digit linkages using the encoders of the motors. The arm moving downward to slam the gripper is then accel-

[3]Python script available online: `https://github.com/HKUST-RML/high_speed_scooping`

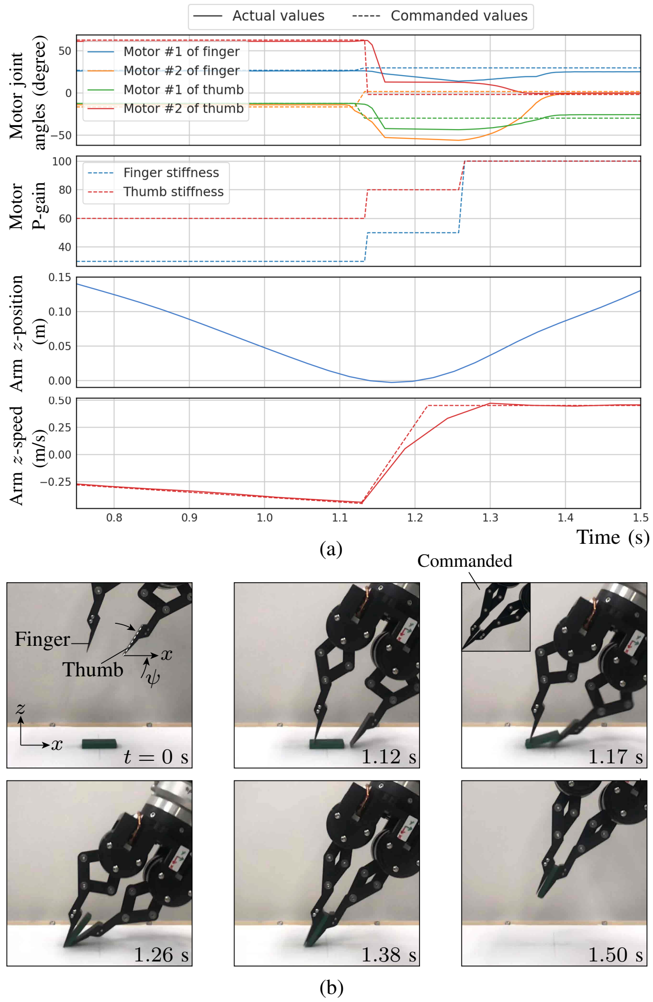


Fig. 4. Timeline of high-speed scooping presented with (a) the time plots of the robot's motion parameters and (b) a corresponding sequence of photographs.

erated upward to stop it from pressing the surface too hard.

3) *Interact with Object* ($t = 1.17$ s): At the instant of the collision detection, the gripper is commanded to close by moving the thumb's tip towards the fingertip (see the change of the motor command in the top plot in Fig. 4(a)) with larger stiffness values (see the change of the P-gains in the second plot in Fig. 4(a)). As the gripper closes, the finger keeps pushing down on the object and the thumb slides on the surface towards the finger and finally penetrates under the object.
4) *Scoop* ($t = 1.26$ s): The object is forced to rotate about the contact point with the ground surface and then enters the workspace of the gripper.
5) *Pinch grasp* ($t = 1.38$ s): Finally, a pinch grasp is obtained. The stiffness values are further increased to secure the object. The gripper itself is shown to move upward with a positive z-speed.
6) *Lift* ($t = 1.50$ s): The gripper takes off from the surface to complete the high-speed scooping task.

Note that the duration of the dynamic interaction is around 0.3 s and the arm does not need to be completely stopped for a finite amount of time (last two plots in Fig. 4(a)).

We applied the operation instanced in Fig. 4 to a range of picking scenarios with various objects both durable (for example, domino block, Go stone, and plastic card) and fragile (for example, snack items such as chips and crackers). The results are summarized in Table I (see also the video attachment). The key findings are as follows:

- **High-speed scooping vs. direct pinch grasping:** When picking thinner objects in particular, our high-speed scooping is more effective than other approaches such as ad hoc direct pinch grasping, in which the gripper's axis is kept normal to the surface and the fingers close parallel to the surface (Fig. 5(a)). Refer to the results with the domino block, Go stone, and thin plastic card in Table I. We note that the control group experiments done with direct pinch grasping were practiced similar to the "smack and snatch" behavior in [23].
- **High-speed scooping of fragile objects:** High-speed scooping of fragile objects is achievable, without damaging the objects, by suitably lowering both the P-gains (i.e. less elasticity) and D-gains (i.e. less damping). See Fig. 5(b) and refer to the results with the cracker and chip in Table I.
- **High-speed scooping vs. low-speed scooping:** When the thumb was controlled to approach to the finger at higher speed, the success rate increased. At lower speed, the thumb was not able to effectively penetrate below the object. See Fig. 5(c). In other words, high-speed scooping outperforms low-speed scooping. Refer to the results with the acrylic block in Table I, where the thumb moved at respectively 0.43 m/s (high-speed setting) and 0.21 m/s (low-speed setting). To enable the change of speed, we applied low-pass filtering to the motor command signals, for adjusting the settling time given a step input.

In addition to the top-down scooping tasks, our technique can also be applied to other scenarios such as picking a book in contact with a vertical surface (Fig. 5(d)). Refer to the results with the book in Table I. In the failed cases, the book dropped after pinch-grasping since the gripper forces were not large enough to support the book's weight.

V. Conclusion and Future Work

This study examined the method of high-speed scooping based on stiffness control and showed its viability through a set of comprehensive experiments. Although our approach does not necessitate a priori knowledge of the environment to interact, the control parameters need to be customized for suitable performance. However, the selection of the parameters is not an easy task, as also understood in the literature. In addition, unmodeled disturbances and dynamic effects may be taken into consideration. In our future work, we have plans to further address these challenges.

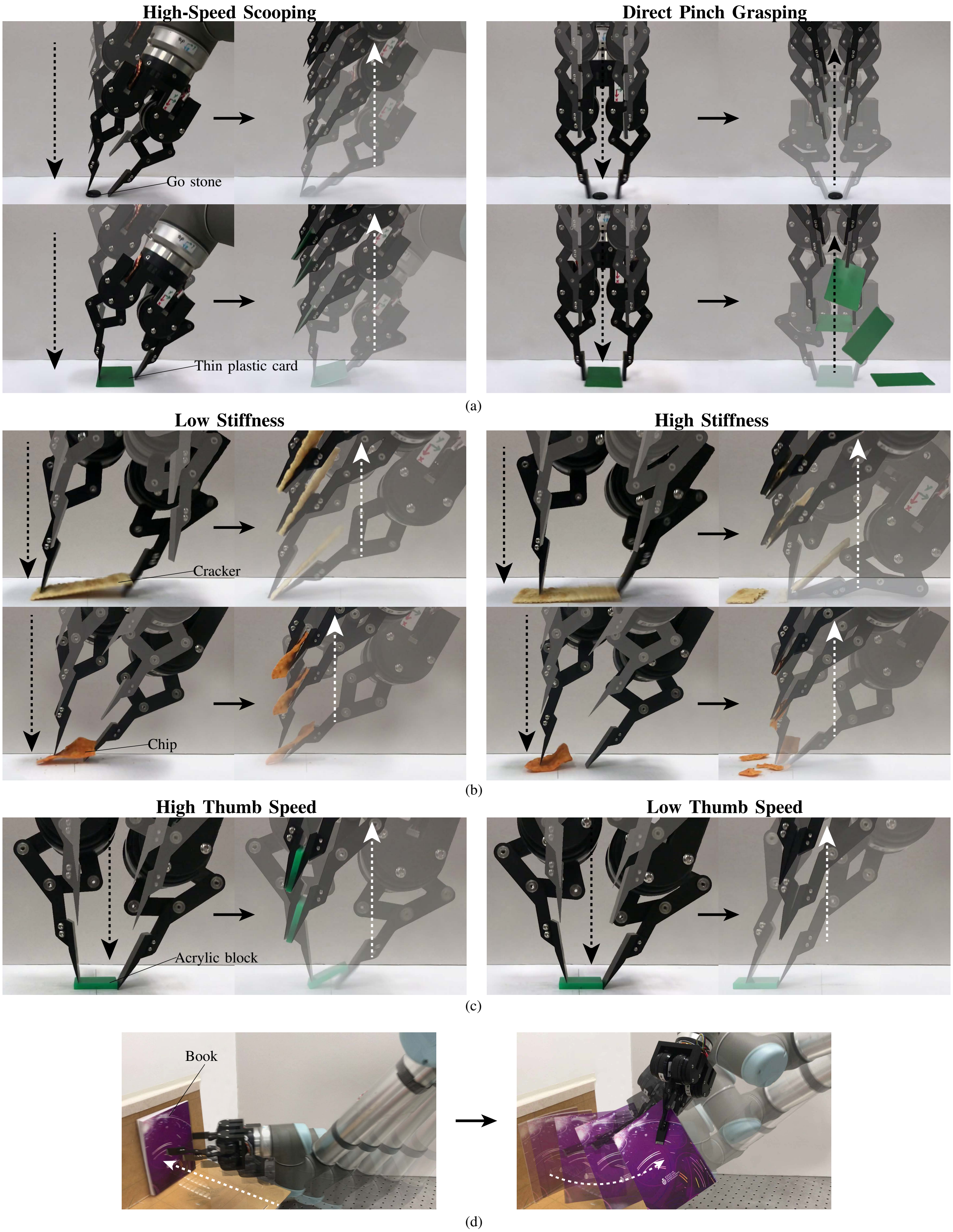
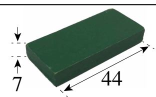
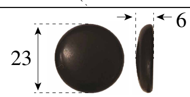
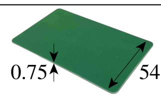
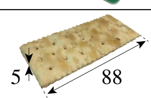
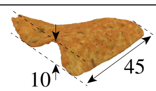
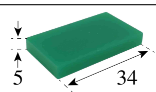


Fig. 5. Time-lapse sequences of high-speed scooping experiments, shown to be more opaque with time. (a) High-speed scooping vs. direct pinch grasping. (b) High-speed scooping of fragile objects. (c) High-speed scooping vs. low-speed scooping. (d) High-speed book picking.

TABLE I

EXPERIMENT RESULTS

Object	Dimensions (mm)	Gripper slamming speed (m/s)	(P-gain of finger, P-gain of thumb) Initial	Final	Thumb attack angle ψ (°)	Success rate
Domino block[1]		0.39	(100, 100)	(100, 100)	N/A	30/30
Domino block		0.44	(30, 60)	(100, 100)	50	28/30
Go stone[1]		0.39	(100, 100)	(100, 100)	N/A	9/30
Go stone		0.44	(30, 60)	(100, 100)	50	30/30
Thin plastic card[1]		0.39	(100, 100)	(100, 100)	N/A	2/30
Thin plastic card		0.44	(30, 60)	(100, 100)	55	29/30
Cracker		0.35	(30, 50)	(80, 80)	60	3/20
Cracker		0.35	(5, 10)	(80, 80)	60	18/20
Chip		0.25	(20, 30)	(60, 60)	60	0/20
Chip		0.25	(0, 10)	(60, 60)	60	17/20
Acrylic block[2]		0.25	(50, 50)	(120, 120)	65	3/10
Acrylic block[3]		0.25	(50, 50)	(120, 120)	65	10/10
Book		0.3	(100, 150)	(300, 300)	45	13/15

[1]Picked with direct pinch grasping [2]Low thumb speed [3]High thumb speed

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