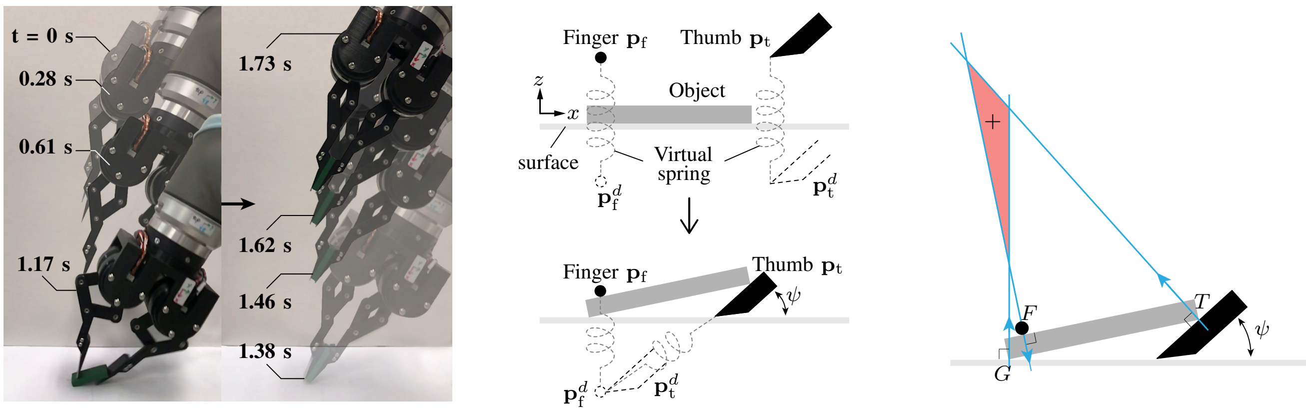
High-Speed Scooping Manipulation Using Controlled Compliance

Ka Hei Mak and Jungwon Seo
The Hong Kong University of Science and Technology (HKUST)
Clear Water Bay, Hong Kong
Email: khmakac@connect.ust.hk, junseo@ust.hk



(a) (b) (c)

Fig. 1. (a) 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. (b) Two-step procedure for scooping through stiffness control. All the bodies (finger, thumb, object, and surface) are assumed to be rigid. (c) Scoopability analysis following [2]. Due to the rigid 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). Scoopability is valid as long as the triangular region shaded red does not vanish.

***Abstract*—The presented study addresses how to perform the manipulation of scooping over a wide range of objects at high speed, termed as *high-speed scooping* (Fig. 1(a)). 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 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 geometric and physical properties of the bodies that physically interact.**

I. High-Speed Scooping: Principles

One viable approach to address the challenges of high-speed scooping is to have the robot emulates the mechanical system that interacts with its environment as desired, according to the formalism of impedance control [3]. Specifically, here the robot is abstracted as a finger-thumb pair (see the point finger and the flat-faced rigid thumb in Fig. 1(b)) and each digit, assumed to move freely, is controlled to render a mass-spring-damper system:

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

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

Eq. (1) represents the 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 $\mathbf{f}$ 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 in the dynamics model.

We then consider how to move the set points of the virtual springs, $\mathbf{p}^d$, in order to achieve desired contact interactions. Fig. 1(b) depicts our two-step procedure. First (top of Fig. 1(b)), $\mathbf{p}_\mathrm{f}^d$ 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 (bottom of Fig. 1(b)), $\mathbf{p}_\mathrm{t}^d$ 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. This will cause the gripper to close and pinch the object.

The suggested strategy poses a question: 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 (Fig. 1(b)), the initial penetration is achievable. This point was also verified in our recent study [2]. Another issue to consider is how to capture the object into a stable final pinch grasp. We place the finger $\mathbf{p}_\mathrm{f}$ on the object such that the object is *scoopable* [2] (Fig. 1(c)); then the object cannot escape 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 geometric information is necessary because of the compliant dynamics and the robustness of scoopability (Fig. 1(c)). Compared to rigid motion control or underactuated control, the contact forces between the bodies interacting can be actively adjusted.

II. High-Speed Scooping: Experiments

Our overall hardware setting is shown in Fig. 2(a). A UR10 arm carries our two-fingered custom-built gripper, inspired by [1], with four degrees-of-freedom (DOF) and direct-drive actuation. Each two-DOF finger is constructed from a symmetric five-bar linkage actuated by two T-Motor GB54-2 motors with no gear train. Using the direct-drive gripper, we implement the stiffness control task in Eq. (1-2) as proportional-derivative (PD) motion control.

The timeline of the implemented process of our high-speed scooping is instanced in Fig. 2(b). The details are as follows:

1) *Approach* (before time $t = 1.12$ s): The gripper is positioned above the object and then slammed on the surface (height unknown) as fast as around 0.45 m/s.
2) *Interact with Environment* ($t = 1.12$ s): The collision between the gripper and the object/surface is detected by proprioception: measuring the displacement of the digit linkages using the encoders of the motors. Meanwhile, the angle of attack ψ at the thumb is sensed, also by the proprioception, and adjusted as needed. The arm moving downward to slam the gripper is then accelerated 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 with larger stiffness values (see the plots in Fig. 2(b)). 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 by the arm with a positive z-speed.

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.

We applied the operation to a range of picking scenarios with various objects[1]; see Fig. 2(c). The results show that our high-speed scooping, with success rate 87/90, can be more effective in picking thin objects than other approaches such as ad hoc direct pinch grasping, with success rate 41/90, and applicable to picking fragile objects too (see the picking of the cracker in the figure).

[1] [Online video]: https://drive.google.com/file/d/1qP3fuFKnlvbISacJgcBIA0HoCvugLJ-I/view?usp=sharing

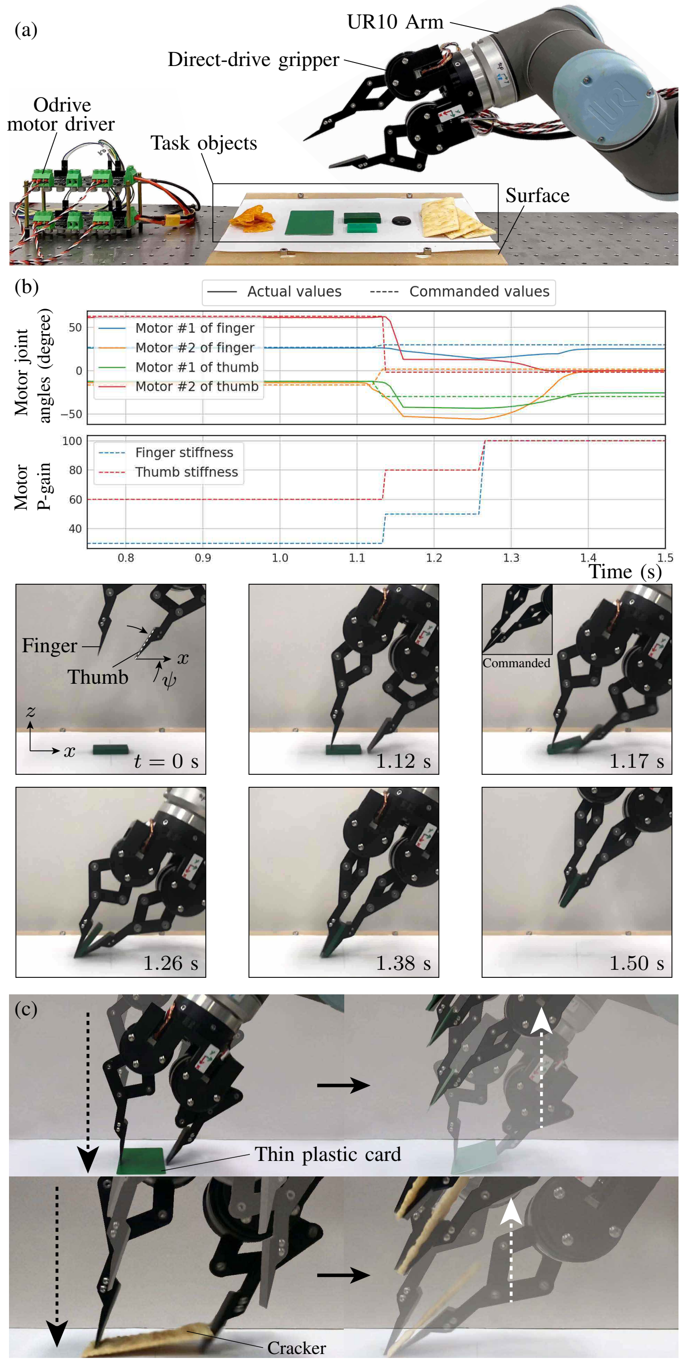


Fig. 2. (a) Experiment setting. (b) Timeline of high-speed scooping with the time plots of the gripper's parameters and a corresponding sequence of photographs. (c) Time-lapse sequences of picking a thin plastic card and a cracker with high-speed scooping, shown to be more opaque with time.

References

[1] Ankit Bhatia, Aaron M Johnson, and Matthew T Mason. Direct drive hands: Force-motion transparency in gripper design. In *Robotics: science and systems*, 2019.

[2] Tierui He, Shoaib Aslam, Zhekai Tong, and Jungwon Seo. Scooping manipulation via motion control with a two-fingered gripper and its application to bin picking. *IEEE Robotics and Automation Letters*, 6(4):6394–6401, 2021.

[3] Neville Hogan. Impedance Control: An Approach to Manipulation: Part I—Theory. *Journal of Dynamic Systems, Measurement, and Control*, 107(1):1–7, 1985.