A Dexterous Robotic Hand for In-Hand Manipulation of Long, Thin Objects

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***Abstract*—This work concerns dexterous robotic manipulation of long, thin objects. It is inspired by how human workers handle steel rods to build cage-like structures used in construction[1]. A typical scenario involves a human worker turning and shifting the steel rod within the hand to prepare it for assembly before fastening it to an existing structure. Motivated by this, we present a low-cost robotic hand (or "gripper"), which uses a roller fingertip and direct-drive actuation to dexterously and compliantly manipulate long, thin objects in quasistatic or dynamic manner. The reliability of our gripper's operations is then confirmed through a set of experiments performed in an open-loop manner.**

I. RELATED WORK

This work is concerned with robotic in-hand manipulation, which refers to the capability of turning and shifting an object within a robot hand [1]. In-hand manipulation can be achieved by interacting with an object through sliding contacts [2, 3], fixed or rolling contacts [4, 5, 6] and breaking-and-making contacts [7]. In this work, our goal is to develop in-hand manipulation capabilities for long, thin (or "slender") objects. Previously, a range of manipulation techniques for slender objects have been proposed to perform tasks such as picking [8], placing [9] and transport [10]. Some manipulation capabilities to be presented will take advantage of finger stiffness control. Both controllable (that is, "active") and non-controllable (that is, "passive") finger compliance have been shown to benefit robot manipulation [11, 12]. Recently, soft robotic hands, which feature passive compliance, were used to demonstrate challenging in-hand manipulation skills [13, 14].

Sec. II describes our robotic gripper system for manipulating long, thin objects. In Sec. III, we present a set of experiments to test our gripper's capabilities.

II. GRIPPER SYSTEM

A. Gripper Design

Fig. 1 shows our robotic gripper. It consists of two fingers. Finger #1 features an active roller fingertip. A small DC gear motor that comes with an encoder is installed inside the roller and moves it in a position-controlled manner. The design for the roller fingertip is inspired by the study presented in [6]. A servo motor, whose axis of rotation is perpendicular to the roller's motion axis, is attached to the roller frame to move it between horizontal and vertical configurations. The roller is covered with a rubber material to provide a high-friction surface for manipulation. Finger #2 features a passive fingertip, which is driven directly (that is, without gearing) by a brushless DC gimbal motor, through a one-DOF linkage mechanism. The linkage mechanism allows finger #2 to both close the gripper or cross over finger #1 (the inset in Fig. 1 shows this). A V-shaped groove around the passive fingertip helps restrain curved objects.

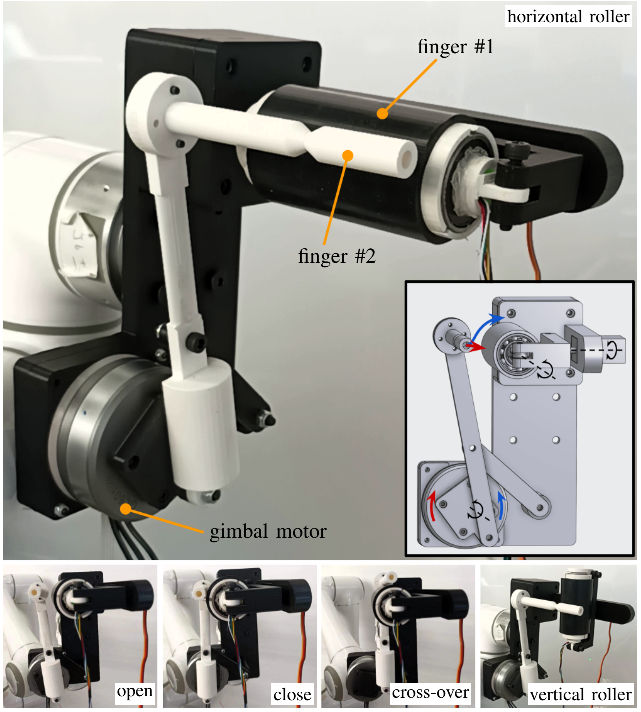

Fig. 1. Our two-fingered robotic hand in different states. States "open", "close" and "cross-over" are obtained by moving finger #2. Starting from an "open" state as shown in the inset, the hand can transition to "closed" ("cross-over") state by moving finger #2 along the red (blue) arrow.

Both motors on finger #1 are controlled using an Arduino board and require 9V DC power. The gimbal motor on finger #2 is controlled using a SimpleFOC[2] driver and requires 24V DC power. An AS5600 hall-effect encoder fixed on the back of the motor keeps track of the motor's position. The driver is programmed such that the motor operates in a position-controlled manner, but its "rigidity" of motion, or stiffness,

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[1] Video available here: https://drive.google.com/file/d/1InOyPlnzbtK7kKHAfzdm9eFbMOJ6UFZk/view?usp=sharing

[2] https://simplefoc.com

can be modulated by changing the controller's error gain. This allows the finger to compliantly interact with a held object. Our software written in Python encodes high-level gripper behavior, such as its different states, and provides a common interface to control its actuators through position or stiffness control. Table I lists the key gripper specifications. The opening range of the gripper sets lower and upper bounds on the thickness of the object that can be manipulated with the gripper. The gimbal motor and its driver make up one-third of the total cost of the gripper (∼$150, combined).

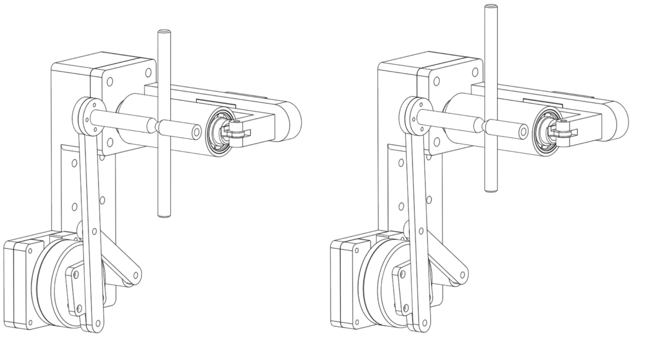
TABLE I
GRIPPER SPECIFICATIONS

Weight	0.7kg
Degrees of freedom	3
Opening range	0 - 15 (mm)
Dimensions (length × width × height)	20 × 12 × 20 (cm)
Cost	$500

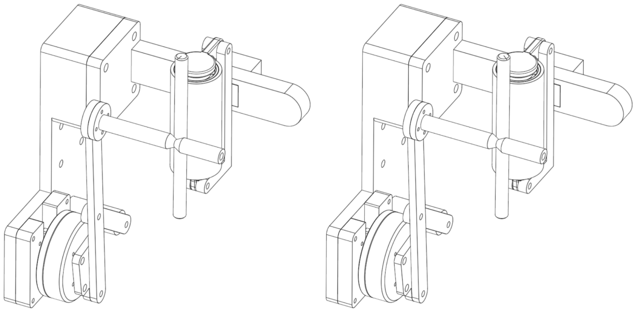
B. Manipulation Capabilities

Fig. 2 shows three planar operations performed with the gripper on a round, slender object model. The "shift" and "spin" operations shown in Figs. 2(a) and 2(b) require identical actuation (rotation of the fingertip roller), but the roller needs to be oriented differently with respect to the object: for shift (spin), the roller's motion axis should be arranged perpendicular (parallel) to the object's longitudinal axis. A successful spin operation additionally requires finger #2 to restrain the object from escaping by accommodating its curved part in its V-shaped groove. Both shifting and spinning are quasistatically stable as the fingers never lose contact with the object. A "twirl" operation (Fig. 2(c)) requires the gripper to transition between its close and cross-over states. This operation is not quasistatically stable because the gripper needs to pass through its open state (recall Fig. 1) in which the fingers can break contact with the object. So for a successful twirling operation, finger #2 needs to: (a) move rapidly enough to keep the object dynamically stable and, (b) timely regrasp the object as it falls under gravity. The high-speed, direct-drive actuation for finger #2 is suited for this task.

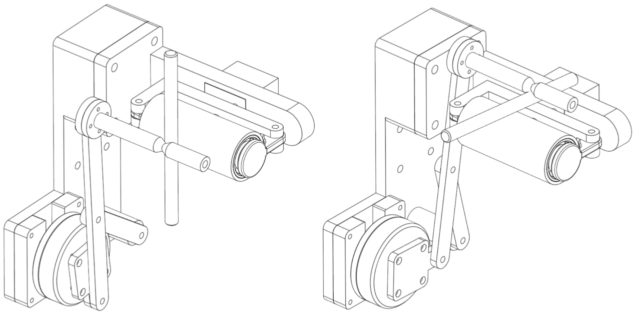
In addition to the three motion primitives described above, the gripper can also manipulate the object through "pivoting". Pivoting manipulation refers to rotation of the object about an axis passing through the two finger contacts [15]. While it may be possible to actively perform pivoting by reorienting the roller frame, here we are interested in the possibility of passive, dynamic pivoting that uses gravity as an actuation resource. For successful pivoting like this, the gripper will need to hold the object gently between its fingertips, such that the object can fall forward under gravity like an inverted pendulum. The gripper may also be required to "catch" the object in a desired configuration by timely switching to a firm grasp such that the frictional wrenches produced at finger-object contacts are able to balance the wrench of gravity. Our gripper's ability to modulate finger stiffness will be critical for achieving passive, dynamic pivoting.



(a) shift



(b) spin



(c) twirl

Fig. 2. Our gripper's manipulation capabilities for a round, slender object model. Operation "shift" ("spin") results in translation (rotation) of the object model along (about) its longitudinal axis.

III. EXPERIMENTS

First, we test shift, twirl and spin operations on an ordinary pen object. The gripper initially holds the pen from the middle, its longitudinal axis roughly aligned with gravity (see the first panels in Fig. 3 for experiment setup.) For each operation, we conduct 10 trials in a row. Each trial involves sequential execution of the manipulation operation in forward and reverse directions. A trial is considered successful if both forward and reverse operations are successful. In shift and spin, the roller is rotated by a small, fixed amount in clockwise and counterclockwise directions. In twirl, the gripper dynamically transitions back and forth between closed and cross-over states. Fig. 3(a) shows successful forward twirl operation

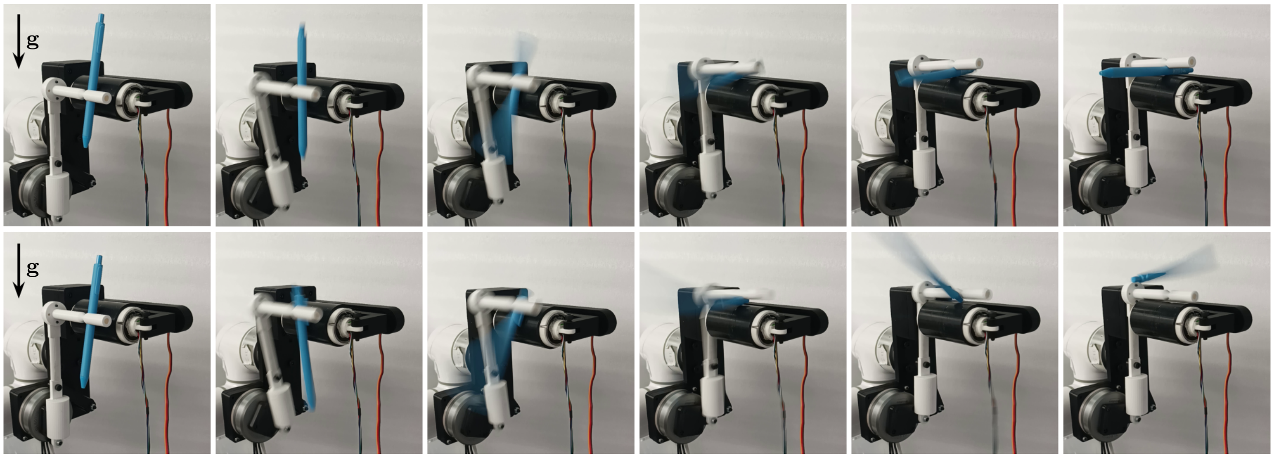


Fig. 3. (Top row) Successful twirling. (Bottom row) Unsuccessful twirling.

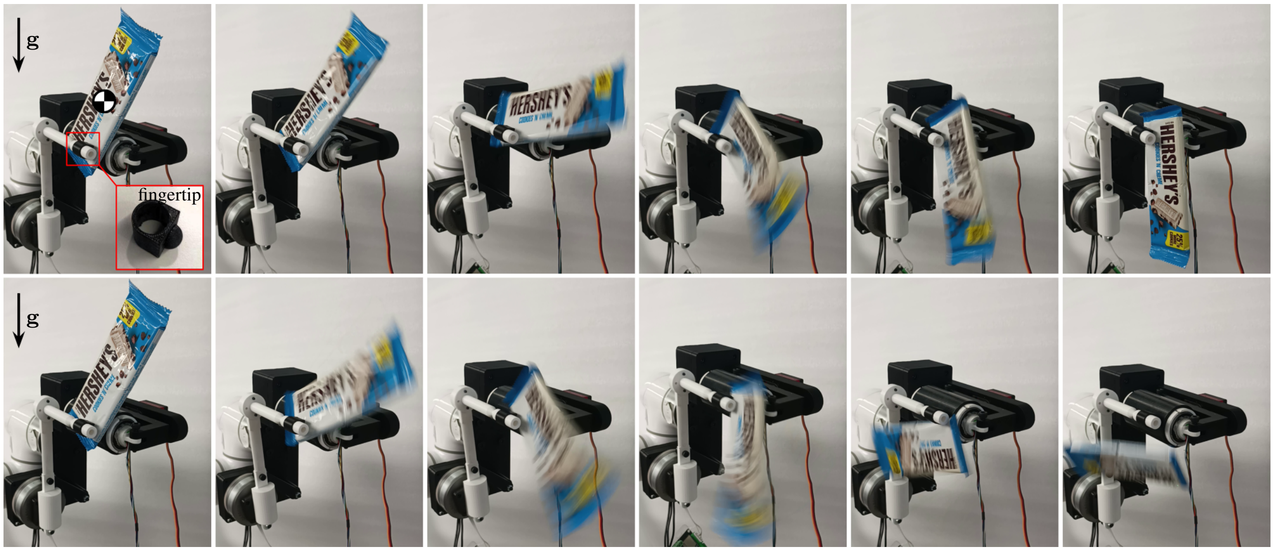


Fig. 4. (Top row) Successful pivoting. (Bottom row) Unsuccessful pivoting.

performed on a pen object that takes it from an initial vertical configuration to a final horizontal configuration in a fraction of a second. In Fig. 3(b), the forward twirl operation fails as finger #2 attempts to regrasp the object too close to the edge (see the last two panels).

Our experiment results suggest that the shift operation can be performed most reliably as all 10 trials resulted in success. A lower success rate (7/10) was observed when performing the spin operation: in failed trials, the moving roller was able to dislocate the pen out of the V-shaped groove. We think that this can be resolved with better finger cavity design that adequately restrains the object. We also repeated the experiments with a lower finger #2 stiffness. The performance of shift and spin operations was generally unaffected (10/10 and 6/10, respectively), but success rate for twirl operation dropped significantly (2/10). At even lower finger #2 stiffness, twirling failed to happen at all as the finger didn't move rapidly enough to timely regrasp the object. Table II summarizes the results of our experiments.

TABLE II
EXPERIMENT RESULTS

Motion primitive	Success rate	
	High stiffness	Low stiffness
Shift	10/10	10/10
Spin	7/10	6/10
Twirl	8/10	2/10

Second, we test pivoting on a thin chocolate bar object. Compared to the curved surface of the pen, the flat faces of the chocolate bar allowed for a more secure pivoting demonstration. The top-left panel in Fig. 4 shows our experiment setup. Here, the geometry of contact between finger #2 and the object is modified to facilitate pivoting. In particular, a hemispherical fingertip accessory is installed on finger #2 to compactly redistribute gripping forces, giving the object tendency to rotate about its contact with the finger. The geometry of contact between finger #1 and the object is left unchanged. Initially, the object is held between the fingers such that it is leaning forward and its center of mass is located above the finger supports. Then, the pivoting operation is executed in an open-loop manner in two steps: First, the grip on the object is loosened to allow it to rotate between the fingers by falling under gravity in a passive, dynamic manner. Second, after a brief pause, the grip is tightened to stop the object from rotating any further. The duration of the pause can be favorably adjusted to achieve a desired final configuration of the object. In our experiments, a pivoting trial is considered successful if the object can be securely rotated to a final configuration in which its center of mass is directly under the finger supports. The top row in Fig. 4 shows an example of a successful pivoting attempt. Between first and second panels, the grip on the object is loosened so that it dynamically rotates under gravity. Between fifth and sixth panels, the grip is tightened to catch the object in the desired configuration. The bottom row in Fig. 4 shows an unsuccessful pivoting attempt. Here, a late grip tightening action results in the object falling off the fingers.

In total, we conducted 26 pivoting trials (at the beginning of each trial, the object was manually placed within the gripper fingers in a suitable configuration.) Only six of those trials resulted in successful pivoting like the one shown in Fig. 4. Eleven trials resulted in failure from an early grip tightening action and six trials resulted in failure from a late grip tightening action. In the remaining three trials, the object did not start to pivot, possibly due to its improper initial positioning. The deformed shape of the chocolate bar after repeated experiments might also have contributed to this failure mode. Considering that the majority of the failures result from an ill-timed grip tightening action, we think that the performance of the pivoting operation can be significantly improved by incorporating feedback (visual, tactile, etc.)

A method to automatically change shape of the fingertip to facilitate a given motion primitive can be incorporated in our gripper. See [16] suggesting one such method. Future work will develop a manipulation planner that concatenates individual in-hand motion primitives to achieve desired object configuration. Robustness of manipulation plans will be promoted through vision-based feedback control.

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