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IN-HAND MANIPULATION PRIMITIVES FOR A MINIMAL, UNDERACTUATED GRIPPER WITH ACTIVE SURFACES

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ABSTRACT

Dexterous in-hand manipulation tasks have been difficult to execute, even with highly complex hands, as the object grasp stability needs to be maintained while it is displaced in the hand workspace. Researchers have shown that underactuated, adaptive hand designs can effectively immobilize objects with simple actuation and open-loop control schemes, but there have been few cases where underactuation has been leveraged to enhance in-hand manipulation. In this work, we investigate the performance of a gripper utilizing a thumb with an active, conveyor surface and an opposing, underactuated finger with passive rollers, for a variety of manipulation tasks and range of objects. We show that consistent, repeatable object motion can be obtained while ensuring a rigid grasp without a priori knowledge of the object geometry or contact locations, due to the adaptive qualities of underactuated design. Many dexterous in-hand manipulation examples with their anthropomorphic equivalents are examined, and simple, open-loop control schemes to optimize the repeatability of these tasks are proposed.

INTRODUCTION

Many researchers [1], [2] have implemented underactuation in robotic hand design to produce adaptive, grasping behavior, enabling effectors to secure objects of different geometries with only minimal, open-loop control. However, tasks other than pick-and-place operations often require more than just grasp acquisition. For example, objects may need to be readjusted within a grasp to secure the object in a more robust grip, to expose particular subsections of the grasped object for use, or to perform minor repositioning that may be beyond the arm's capabilities [3]. It would be desirable to perform these tasks while minimizing additional mechanical or control complexity.

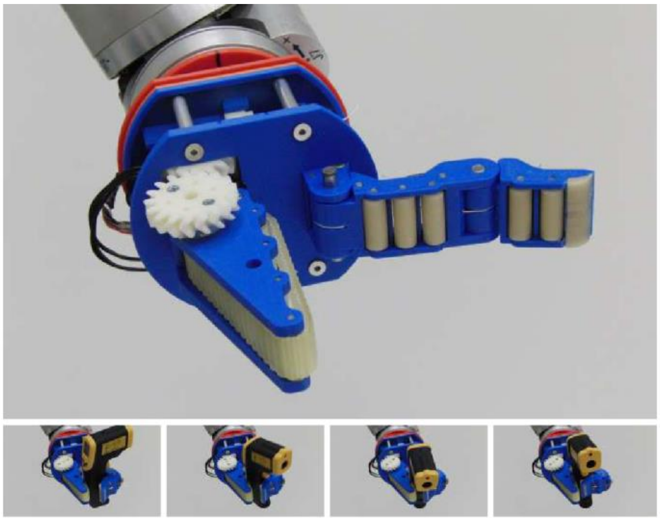

Fig 1. The proposed active surfaces gripper uses an actuated belt opposite an underactuated finger with passive rollers to generate dexterous manipulation capabilities

Dexterous, in-hand manipulation typically requires the effector to maintain grasp stability as the object is displaced within the hand workspace. To accomplish this, past efforts have focused on multifingered-hand designs with a high degree of actuation [4]. Although underactuated hands' passive adaptability can come at the cost of controllability, researchers have shown that mechanical design parameters and actuation schemes can be optimized to produce dexterous behaviors despite the reduction in actuators [5]. However, these efforts

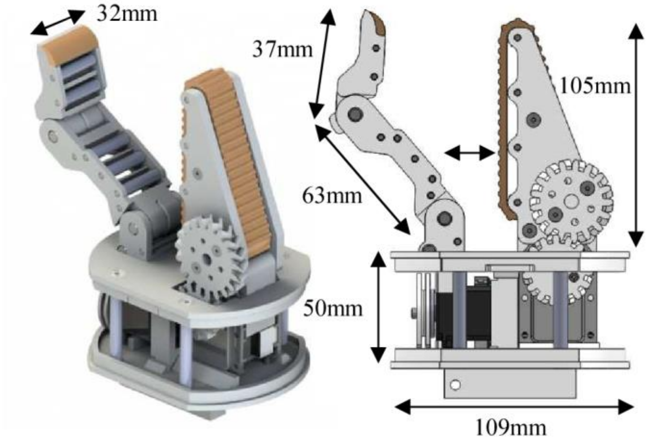

Fig 2. CAD dimensions for the active surfaces gripper. The final prototype is comparable in size and weight (466g) to existing commercial and open-source research end effectors

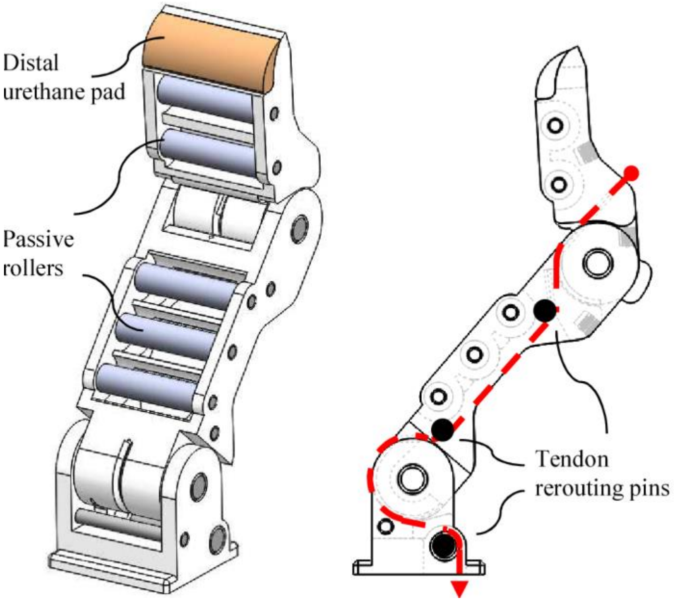

Fig 3. Underactuated finger with passive rollers (2 in distal phalanx, 3 in proximal phalanx) is driven by a single tendon (routing path shown in red) connected to an MX-28 Dynamixel servo. A urethane pad at the distal fingertip aids in the precision grasp acquisition of smaller objects

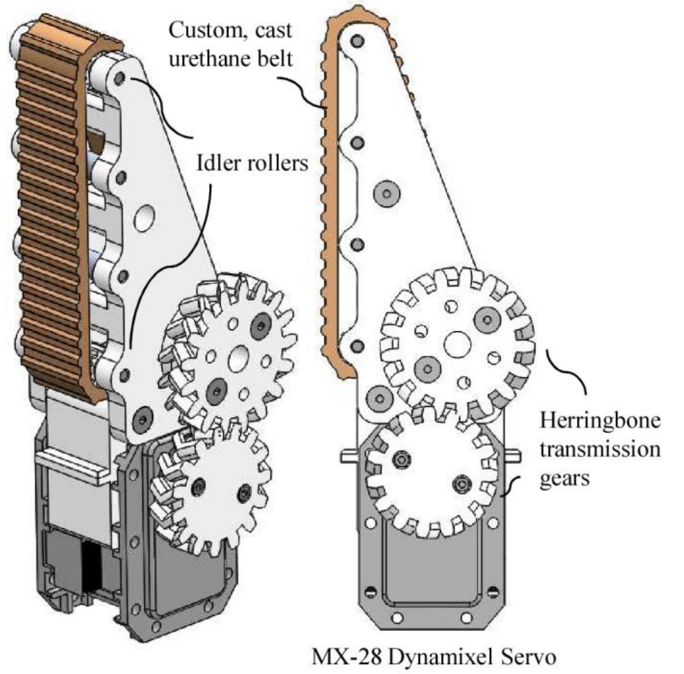

Fig 4. The thumb active surface module is comprised of a cast urethane belt supported by passive idler rollers in front and driven by an MX-28 Dynamixel Servo via printed herringbone gears

still primarily take inspiration from the human hand, in both mechanical structure and control strategies.

Actuated contact surfaces, most commonly driven conveyor-belts, have been implemented in non-anthropomorphic manipulation efforts [6][7] to apply tangential loads onto the object and modulate the contact state between the object and finger surface. Behavior at the object-hand interface can be difficult to control even when the material and kinematic properties are well known [8], so direct and explicit slip control can be beneficial. More recently, these mechanical features have been formalized as *active surfaces*, as found in the Velvet Grippers design [9] in the form of a set of high-friction belt drives. In this study, the *active surface* concept is further studied in a minimal gripper, shown in Fig 1, composed of a static, one-link thumb with a single, actuated belt surface, and an opposing, two-link, tendon-driven, underactuated finger with passive rollers. Its behavior and functionality is compared to that of traditional, underactuated hands, and many dexterous manipulation primitives generally associated with the human hand will be demonstrated with this simple gripper.

MECHANICAL DESIGN AND FABRICATION

The basic dimensions of the prototyped gripper are detailed in Fig 2. The design is built upon the Yale OpenHand library's Model T42 hand [10], comprised of two underactuated fingers in opposition, each independently tendon-driven with a servo. These designs were developed to mainly utilize readily-available, off-the-shelf components, minimize part count, and leverage an accessible, hybrid manufacturing technique that combines 3D-printing and urethane casting [11], [12]. This design philosophy seeks to maximize the durability of printed components and simplify the fabrication process for other researchers.

The two-link, underactuated forefinger uses traditional, revolute pin joints. It is driven by a single agonist tendon anchored at the distal fingertip and actuated by an MX-28 Dynamixel servo [13], which has a stall torque of 3.1 Nm at an operating voltage of 14.8V. Return extension springs are installed at the back of each joint to reset the finger configuration when the agonist tendon is slack. As illustrated in Fig 3, passive rollers on press-fit steel pins are arranged along each phalanx (three in the proximal and two in the distal), with the intended goal of producing frictionless contacts, regardless of the object's material properties. The distal fingertip has a Vytaflex 30 urethane [14] pad to aid in acquiring precision grasps of smaller objects.

Details for the design of the active surface thumb are shown in Fig 4. A custom belt geometry was cast with PMC-780 urethane [15] in a 3D-printed sacrificial mold, a process detailed in [12]. This was used in lieu of off-the-shelf timing belts to give the user greater design flexibility in designating both the outer contact geometry and the inner belt tooth profile that mates with the drive spindle. For example, though not investigated in this effort, a non-uniform, outer belt contour could have been an alternative design option. A series of four idler rollers support the belt along the thumb's front surface, and the belt itself is driven by a toothed spindle at the back of the thumb base. In this design iteration, the mating between the belt and the toothed spindles were not exact, due to limitations in printer resolution, affecting both the drive spindles and the molds for casting the belt. Consequently, intermittent slippage could occur during actuation of the active surface. A pair of printed herringbone gears completes the actuation transmission between the second MX-28 Dynamixel servo and the belt. Such gears are advantageous for printed processes, as they self-center, and more than a single pair of teeth mesh at any instant, reducing the amount of shear stress on each gear tooth. Switching between continuous rotation and position-control modes on the Dynamixel servo allows for multiple operating modes on the thumb. However, the belt will principally be driven with a constant velocity for the tasks described in this paper.

Aside from feedback inherent to the Dynamixel servo, no additional sensors were implemented in either the forefinger or thumb. For open-loop grasp acquisition, the forefinger in these hand designs is typically driven with constant torque until the finger is immobilized due to contact with the object and other hand subcomponents, at which point the tendon position is locked through the servo to avoid overheating. The hand can drive the thumb active surface in either direction with a range of different speeds.

MANIPULATION CAPABILITIES

While contact on all finger surfaces may not be guaranteed in all manipulation cases, the model presented in Fig. 5 is representative of the expected in-hand manipulation behavior for the proposed hand design. In contrast with traditional, anthropomorphic hands, the tangential force along the thumb surface is independently controlled, assuming the forefinger applies sufficient normal force to maintain no-slip conditions between the thumb and object. In this way, functional task requirements of maintaining a stable grasp and displacing the object within the hand workspace can be decoupled, fulfilled by the underactuated forefinger and the active surface thumb, respectively.

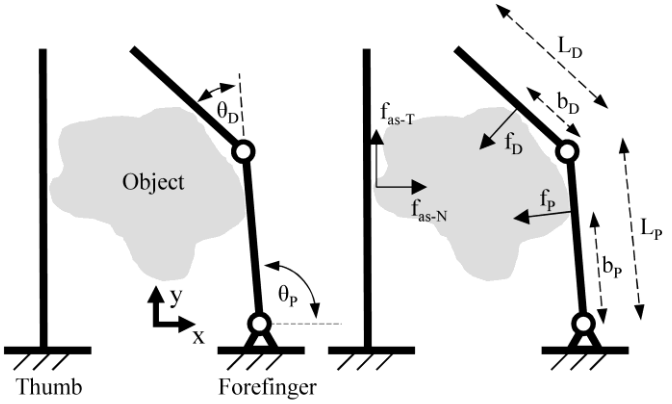

Fig 5. Simple grasp model for the proposed active surfaces gripper, where each forefinger link exerts a normal force on the object. The tangential force $f_{as\text{-}T}$ is independently controlled via the active surface.

The modeling of the underactuated, two-link finger implemented here has been thoroughly studied in literature [1] and will not be restated in detail here. The following summarizes the relationship between the contact normal forces $\overrightarrow{f_e}$ and net joint torques τ:

$$\tau = J_C^T \vec{f_e} \tag{1}$$

$$J_C = \begin{bmatrix} b_P & 0 \\ b_D + L_P\cos(\theta_P) & b_D \end{bmatrix} \tag{2}$$

$$\vec{f_e} = [f_P \quad f_D] \tag{3}$$

Due to the passive rollers, it is assumed that no tangential forces can be applied by the forefinger. In principle, an underactuated two-link finger driven by a single actuator will continue to close inwards until motion is no longer possible, due to physical constraints between the hand features and object. The final configuration typically has the underactuated finger wrapped around the object, fixturing it in place relative to the hand coordinate frame. Mechanical parameters are chosen to avoid ejection cases, where the contact with the object is lost during grasp acquisition or manipulation.

According to the hand-centric manipulation taxonomy by Bullock et al [16], tasks commonly associated with dexterity generally fall under the subcategories of *Within-Hand* and *Motion-at-contact*, such that the hand components move relative to its base and the object reference frames move relative to the contact points, respectively. A subset of cases, referred to as finger-gaiting, contact with the object may be lost and re-established to effectively extend the workspace of individual fingers [3]. An active surface has the unique property that contacts are broken and established continuously, as the actuated motion is generally orthogonal to the forces maintaining contact. In this section, dexterous manipulation

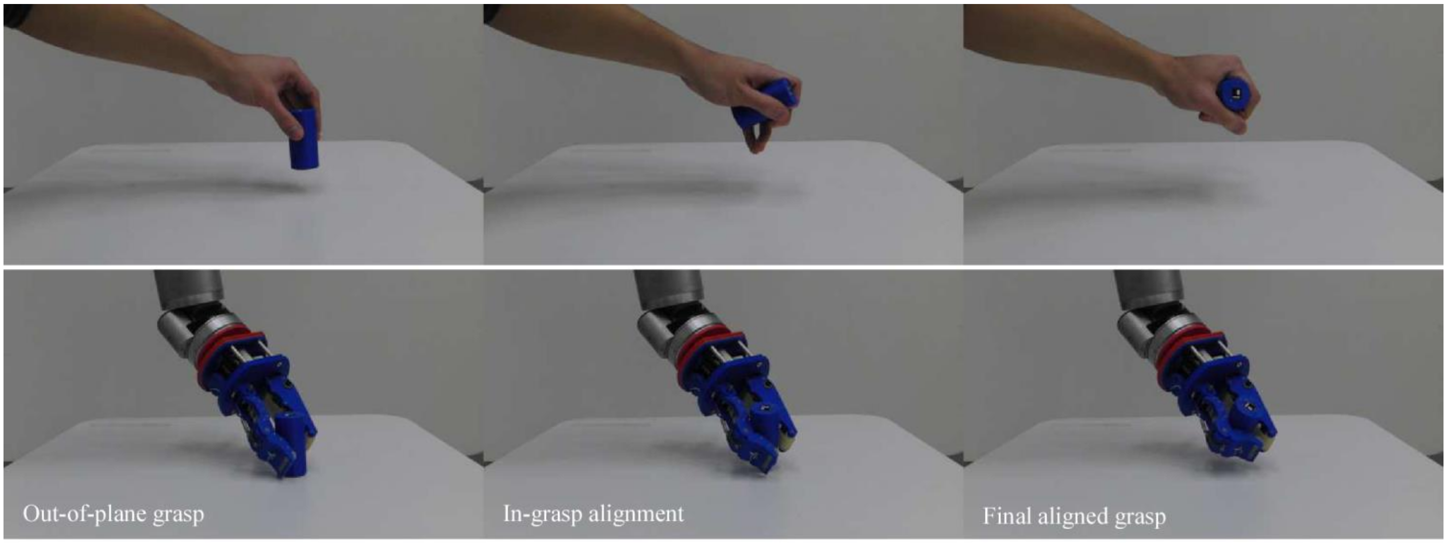

Fig 7. **Out-of-plane Alignment:** Object is initially grasped out-of-plane and is realigned securely to the hand surfaces

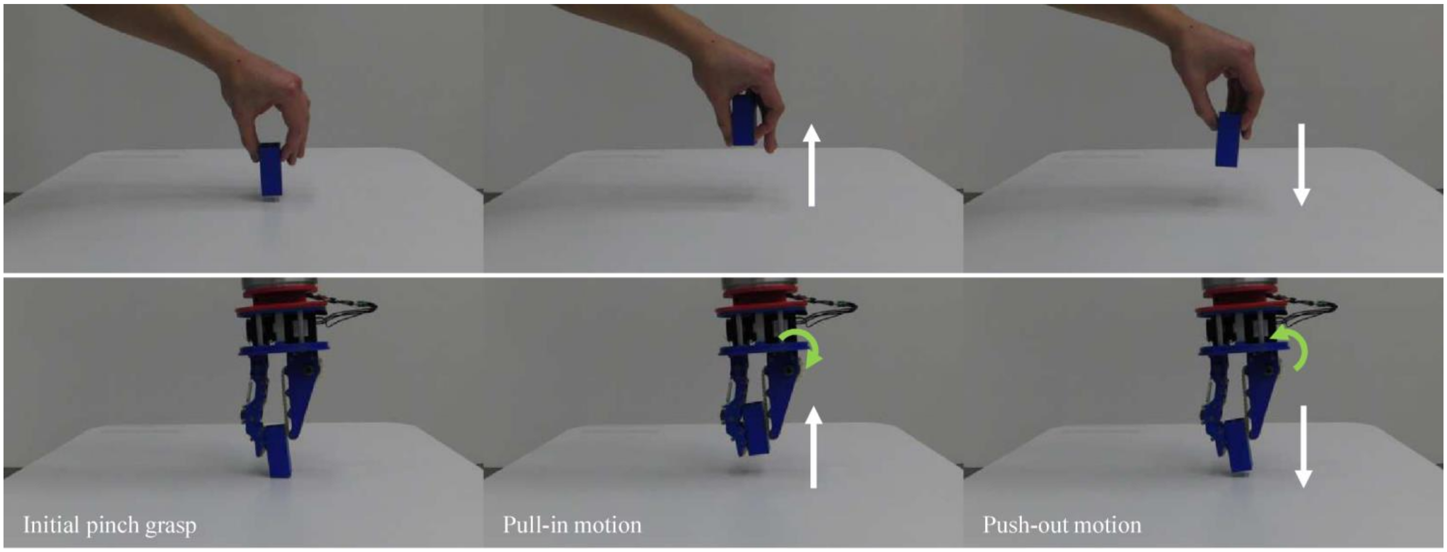

Fig 8. **Pull-in/Push-out:** Object can be displaced towards and away from the palm or base of the hand. Green arrow denotes the rotation of the main drive spindle for the active surface

strategies are demonstrated by both the prototype end effector and a human hand, to validate the effectiveness of active surfaces in extending the capability of simple grippers.

Manipulation Primitives

- **Surface-constrained Sliding:** Fig. 6 details a nonprehensile manipulation strategy where a virtual finger slides an object on some surface. In the human example, multiple fingers are used to ensure that at least one is maintaining contact with the object at all times, keeping it pinned against the table surface. In contrast, the active surface maintains contact with the object at all times as long as the gripper is held rigidly. In both the human and robot cases, the task can be completed with the arm and wrist held static.

- **Out-of-plane Alignment:** Some grasps may initially be stable but sub-optimal. For example, planar grippers may at first secure an object out-of-plane, as shown in Fig. 7. The object can be pulled inwards until its principal axis is aligned against some internal hand structure, usually the palm. In the case of the gripper, which effectively has no palm, the depth of the proximal finger link enables the object alignment. This suggests that active surface can be used to effectively localize the object within the hand workspace for a range of initial grasp poses.

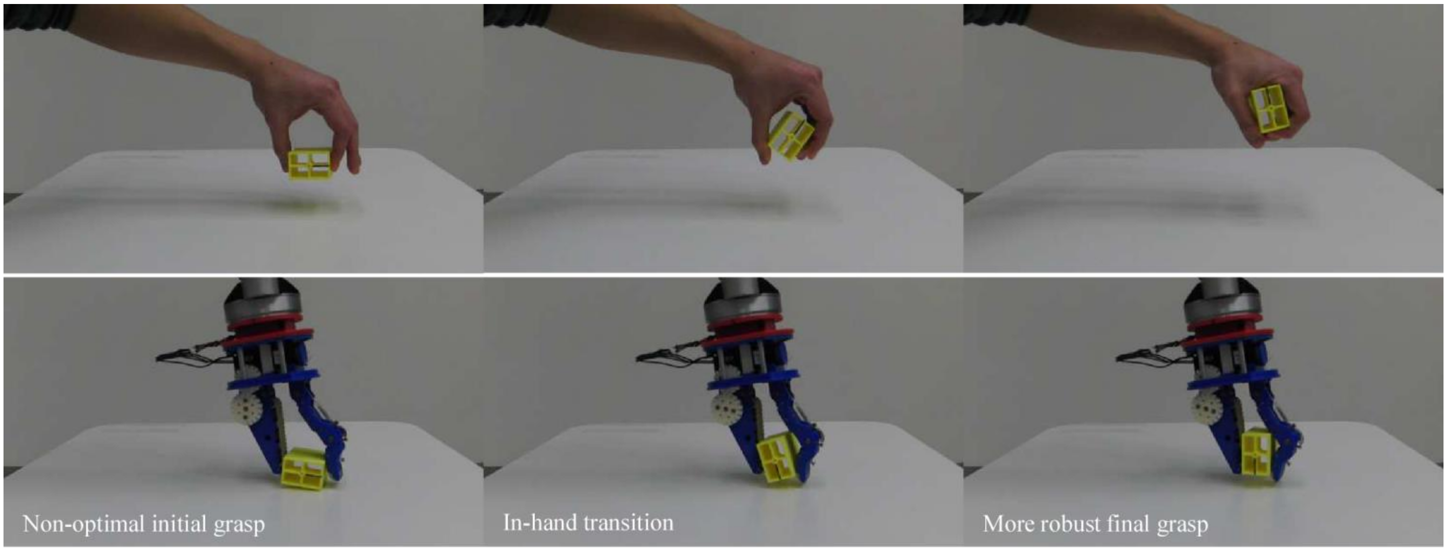

Fig 9. **Grasp Improvement:** Transitioning from a relatively weaker precision grasp into a more secure wrap-grasp for an irregular object

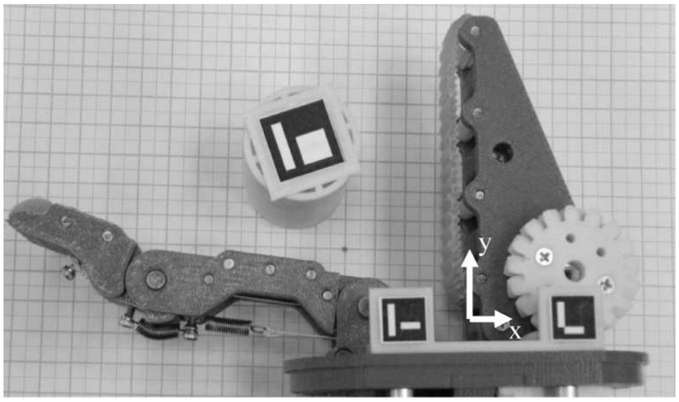

Fig 10. Fiducials were attached to both the hand and a test object to track the object trajectory during an open-loop grasping procedure.

- **Pull-in/Push-out:** The object may need to be pulled in towards the hand palm or base to further secure the object, or it may need to be pushed outwards, either to expose some section of the object for use, or for controlled release. The example of this task shown in Fig. 8 also illustrates how both the human hand and gripper change the points of contact on the object. As with the nonprehensile sliding manipulation, the gripper can change contact points without releasing or resetting any of the fingers.

- **Grasp Improvement:** Fig. 9 shows an example where the object is rotated within a stable grasp into a more robust grip by increasing the area of contact between the object and hand. For irregular object geometries in particular, there may be certain object poses relative to the hand base where the hand can more efficiently resist external wrenches on the object, especially in physical cases where the actuator output may be limited.

A video summarizing the manipulation primitives presented in this section can be found at https://youtu.be/JPCoy06VT1g

Grasp Repeatability

As detailed in work done on the Velvet Fingers [9], [17], active surface control can also be a means of modulating the slip behavior at contact, which consequently can affect the stable grasp configuration. While the passive adaptability of underactuated hands helps ensure contact between the hand and the object, the stable pose of the latter relative to the former may have some significant variance. It may be critical to not only guarantee that an object is secured to the effector, but also how it is fixtured.

Aruco fiducial markers [18] were affixed to the gripper base and a 35mm diameter test object, as summarized in Fig. 10, to visually track the object trajectory during grasp acquisition. The object was randomly placed within the graspable range of the gripper, and the forefinger was commanded to close with a constant actuation force for a duration of 3.5 seconds. This evaluation was repeated for both an actuated and unactuated thumb. In the actuated trials, the thumb active surface was run at a constant velocity inwards towards the base.

The y-coordinate for the object trajectories in these trials are presented in Fig. 11. For both actuated and unactuated trials, there is an evident tendency for the gripper to shift the object toward y=60mm. However, in both actuation schemes, there are trials where the object path converges to different stable poses as a result of friction and/or jamming. An actuated thumb surface minimizes the number of such cases and reduces the range of possible stable grasp poses. Even in the trials where the object does not reach the expected pose, it is evident that the active surface is driving the object away from non-optimal grasp states.

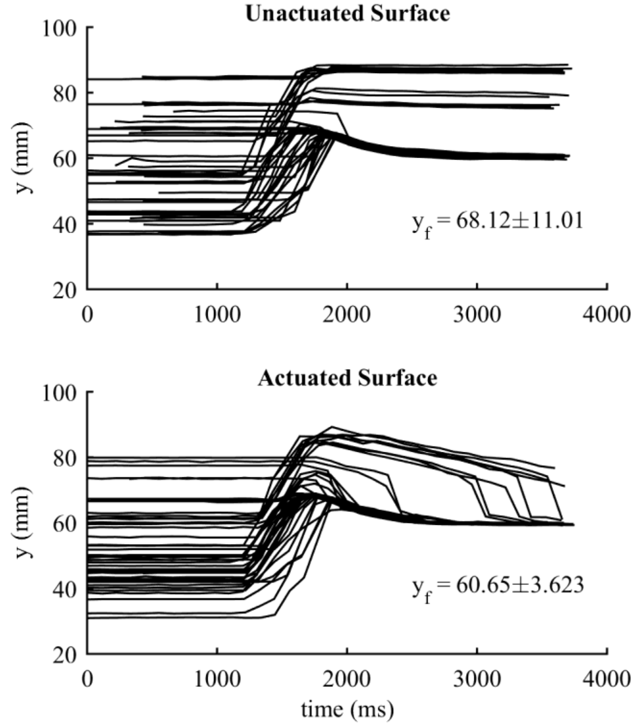

Fig 11. Y-coordinates for 35mm diameter test object during an open-loop, planar grasping task, repeated for a range of initial starting poses, with the thumb surface both active and inactive. The gripper was able to localize the object more effectively with an active surface

CONCLUSION AND FUTURE WORK

This study suggests that non-anthropomorphic features, namely an actuated conveyor belt surface, can enhance the dexterous manipulation capabilities of simple grippers. The capacity of a driven belt to form new contact points without fully disengaging from the object makes it a useful mechanical addition, especially in combination with an adaptive opposition finger that can maintain stable closure conditions for different object geometries. Several manipulation examples, some of which commonly associated with finger-gaiting, were demonstrated with this end effector. The thumb active surface also noticeably improved the grasp repeatability, minimizing the object pose variability within the hand workspace. Notably, the active surface could be implemented simply and modularly, extending an existing open-source gripper design, without the need for any complex transmissions.

Only basic, planar, open-loop control was investigated for this paper to show the feasibility of dexterous tasks. Many of the demonstrated examples only terminated with the object driven against some mechanical limit. Tactile and/or visual feedback would provide much improved control fidelity and enable more autonomous behavior. In particularly, a more thorough analysis of the passive-alignment and pinch-to-power manipulation primitives would improve performance where the gripper needs to more efficiently resist forces on the object (ie. external impulses or impacts). Future work will also consider the efficacy of active surfaces in more complex hand designs or different hand layouts.

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