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An Active Palm Enhances Dexterity of Soft Robotic In-Hand Manipulation

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***Abstract*— In-hand manipulation is challenging for soft robotic hands, especially in the real world where robots encounter a variety of object sizes and shapes. As such, the role of the palm is crucial, providing stabilizing contact to objects during grasping and manipulation, and controlling the position of objects with respect to the fingertips. We demonstrate an actuated palm capable of enhancing the in-hand manipulation capabilities of a soft hand by better-utilizing limited finger dexterity. With a combination of physical and virtual experiments, we explore the effects of palm diameter and height on in-hand manipulation performance over a variety of object shapes and sizes, and three key manipulation primitive motions. The results of these experiments show that maintaining manipulation capabilities over a large range of object sizes requires the palm's diameter to decrease as a function of its height to prevent interference between the fingers and palm. Based on these insights, we design an actuated palm mechanism that achieves the desired relationship between palm height and diameter using one actuated degree of freedom. Finally, we show that this adjustable palm enables the hand to manipulate a larger range of object sizes and aspect ratios, and its utility is demonstrated in a mid-air shelving in-hand manipulation task.**

I. Introduction

In the ever-more-automated world, we see a growing need for robots to perform dexterous manipulation while remaining adaptable and human-safe. Many common activities of daily living (ADL) require gentle but dexterous motions, such as removing delicate pastries from their packaging, or setting a dinner table [1], while others require simpler, but stronger coarse manipulation such as stocking a refrigerator with delicate produce items. Furthermore, assembly and pick-and-place tasks may require dexterous end-effectors when the environment is unstructured. Given the benefits of compliant hands when dealing with uncertainty in the environment [2], soft robotic hands are a promising approach for both grasping and in-hand manipulation.

Dexterity can be implemented in a soft hand using a number of design techniques, typically focusing on the dexterity or arrangement of individual fingers. On one end of the spectrum, compliant hands such as the Shadow Dexterous Hand [3] or BCL-26 Hand [4] utilize upwards of 20 independent degrees of freedom (DOFs) to achieve high dexterity at the cost of highly complex mechanical systems which can be fragile and difficult to control. Both of these hands are based on anthropomorphic architectures, with fingers that have human-like kinematics. On the flip side, simpler compliant hands such as the iHY hand [5], the RBO Hand 2 [6], and the CLASH hand [7] with six controlled DOFs have been shown to perform very robust grasping in a variety of real-world tasks, but lack the dexterity to maneuver objects within the hand. In a middle-ground approach, we achieved high-dexterity with moderate complexity in our previous work with an 8-DOF soft hand with four 2-DOF fingers [8]. Our design can perform robust grasping and several in-hand manipulation primitives (planar rotations and translations of objects), resulting in enough dexterity to perform complex tasks such as manipulating objects in mid-air.

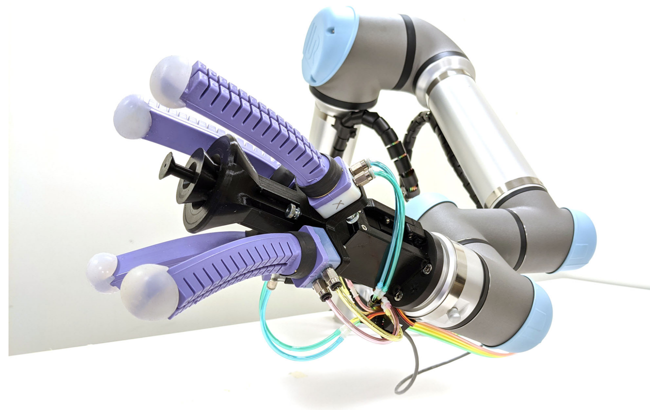

Fig. 1. Our 1-DOF actuated palm can adjust its surface position and diameter to enable in-hand manipulation of a variety of object sizes while preventing interference between the palm and fingers.

In addition to finger designs, the palm can contribute to hand dexterity through controlled shape or position relative to the fingers. The importance of the palm is especially evident in human hands during grasping and in-hand manipulation. For the dominant human hand, the palm provides a higher force contribution than other anatomic areas to the hand's total grip strength [9]. In addition, palm surfaces are sometimes used in robotic grasping to provide stability to objects during power grasps [5], [6], [10] or act as convenient surfaces to support objects during in-hand manipulation [8], but are often omitted entirely in favor of finger compliance [11], [12], [13], [14]. However, this means these robotic hands must rely on finger dexterity alone to grasp and manipulate objects.

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Utilizing an active palm as a movable/deformable contact surface has been demonstrated in a soft hand, but can have limited utility when fingers are extremely dexterous. For example, the BCL-26 Hand has 26 controlled DOF's, with 3 DOF's in the the palm [4]. However, some evidence suggests that humans only utilize five to six DOF's during grasping [15], and seven to nine DOF's during in-hand manipulation tasks [16]. Understanding how to control all 26 DOF's proves challenging, and may not be necessary from a strict task-based perspective.

In this work, we demonstrate a soft robotic hand with an actuated palm capable of increasing in-hand manipulation capabilities by more effectively utilizing limited finger dexterity. We first discuss our soft robotic hand platform and important palm design parameters, choosing to focus on the height and diameter of the palm. Next, we used a combination of physical and virtual experiments to explore the effects of the palm design on in-hand manipulation performance. The results of the design exploration suggest that no single palm design can enable successful in-hand manipulation for all objects. Based on these results, we propose an actuated palm design with one degree of freedom which can change its height and diameter to accommodate a larger range of object sizes. Finally, we demonstrate the palm's utility during manipulation primitives and a complex in-hand manipulation task inspired by stocking display shelves.

II. Achieving High-Quality In-Hand Manipulation

Achieving precise, repeatable, and sufficiently fast in-hand manipulation with a soft robotic hand is challenging due to finger compliance. A few observations can help in designing a system that meets these requirements. Treating in-hand manipulation as a similar problem to multi-limb manipulation, we can observe that the object has its largest range of motion if it is in contact with the end of the manipulator as opposed to the middle. This same rule applies for soft fingers with limited controlled degrees of freedom: a larger dexterous workspace is achieved if objects are manipulated by the fingertips.

Another key insight is found when observing the role of the palm as a mechanical stabilizer for the object. This stabilizing effect creates a "local mechanical ground", giving the hand a foundation to bear the weight of heavy objects. Additionally, the palm constrains the object's pose, which removes uncertainty during in-hand manipulation by reducing the possible number of DOFs in the object's position.

Taken together, these two insights imply that objects are best-manipulated when in contact with the fingertips, and when a palm or external surface provides a stable platform. Thus, we want our palm to be in contact with the object whenever possible. Furthermore, the effect of gravity on a grasped object's rotational stability is minimized when the fingertips make contact close to the object's center of mass.

Finally, the soft robotic hand platform used in this study was demonstrated previously in Abondance et. al [8]. It can achieve planar in-hand manipulation of a variety of objects using a symmetric array of four fingers, each with two degrees of freedom. In our previous work, this hand had a simple passive palm, which produced an inability to support small objects at the correct height to be grasped by the fingertips.

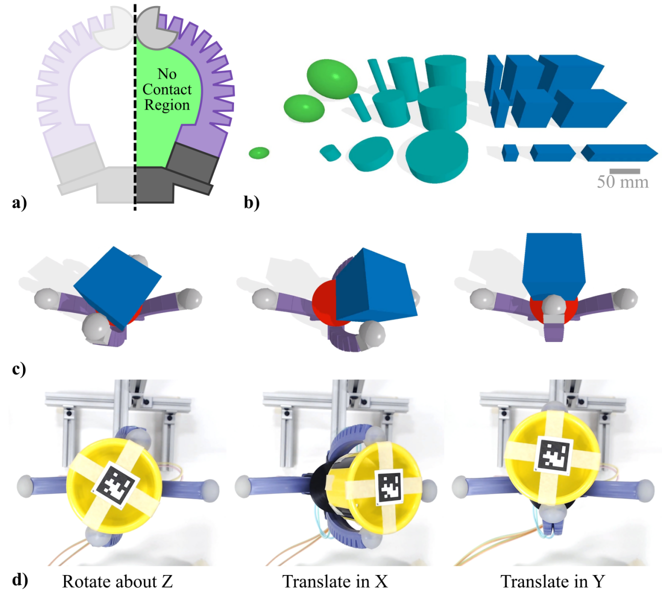

Fig. 2. To evaluate the effect of various design parameters on in-hand manipulation performance, a) we used a simple analysis of the finger's workspace, and b) performed large parameter sweeps using the SoMo framework [17], and validated those sweeps using several isolated experiments on real hardware. b) We tested several simple objects of varying shapes, sizes and aspect ratios, and included three basic in-hand manipulation primitives. Top views of manipulation primitives performed c) in simulation and d) on the real hardware are shown.

Our goal is to achieve these two basic design constraints in our soft hand platform for a variety of object widths and heights, thereby enhancing the hand's manipulation capabilities. To achieve this, we could either 1) add one additional DOF per finger (4 DOF's total in our hand platform) to enable the fingertips to move in and out with respect to the palm, or 2) add 1DOF in a dexterous palm that can move its surface in and out with respect to the fingers. In this study, we chose to investigate the role of the palm for in-hand manipulation.

III. Design Exploration using Passive Palms

To understand the effects of the palm's physical dimensions on the overall in-hand manipulation performance of the hand, we utilized a new simulation platform for soft robots (SoMo, [17]) to perform a large-scale series of experiments on a simulated hand, then validated the observed trends on physical hardware. Examples of these experiments are shown in Figure 2. Overall, the simulations captured the trends in manipulation performance of the hardware platform, and results matched for key phenomena. These experiments validate our intuition about the coupling of palm diameter and height to avoid interfering with finger motion.

To evaluate the grasping and manipulation capabilities of the simulated and actual hardware as a function of the palm design, we defined four metrics related to task performance. The first two metrics are binary checks during each manipulation task. ”Contact success” is true when the fingertips make contact with the object before manipulating, and ”manipulation success” is true if the hand can perform the manipulation primitive for an extended time without dropping the object. These two metrics directly inform palm design: ”contact success” acts as a filter to ensure a wide range of objects can be grasped, and ”manipulation success” refines the design space to ensure in-hand manipulation is possible. Next, for all successful manipulation tasks and objects used, we defined two more metrics related to the object’s dimensions: the minimum object height and width successfully manipulated. These four performance metrics enable use to quantitatively evaluate palm design in a task-relevant way.

A. *Palm Design*

When designing a palm for our soft hand platform, several physical properties of the palm’s surface were considered, but ultimately only the height and diameter were explored in-depth due to their specific utility for in-hand manipulation. The height of the palm’s surface is critical to manipulation performance, as it determines where the fingers make contact with the object. The diameter of the palm is also important for maintaining the range of object sizes that can be manipulated, as it should not interfere with the fingers. Two additional design parameters were considered (the palm’s friction and concavity), but initial testing indicated that the height and diameter were most-promising as long as the palm’s surface has sufficiently low friction.

B. *Experimental Setup*

To ensure no interference between the fingers and palm, we can examine a simple profile of the finger’s inner surface during a grasp of an arbitrarily thin object, as shown in Figure 2a. This profile shape produces an estimate of the maximum palm diameter for a given height. Palm designs within this boundary will not interfere with with fingers during grasping. However, this analysis does not hold during in-hand manipulation tasks due to 3D kinematics of the fingers, so a more comprehensive set of experiments is necessary to fully explore the design space.

To understand the design space in the context of in-hand manipulation, we utilized a new simulation framework (SoMo, [17], [18]) to rapidly explore the effects of these design parameters. In this framework, soft fingers are modeled as hyper-redundant rigid-body serial manipulators with compliant joints. For these simulations, we used the mass, stiffness, and blocked force measurements of the soft fingers from [8] to calibrate the simulated fingers. The calibration from bending beams to discretized links with spring joints is described in [17], and results in actuator-level accuracy in blocked force of 0.28 N, and task-level accuracy of 9% for a complex finger gait [17].

With a sufficiently accurate simulation framework, we explored our palm design space through a series of simulated experiments. Over a variety of objects, the hand was commanded to perform three planar in-hand manipulation primitives using heuristically-designed actuation torque trajectories. While co-design of hand morphology and control would produce a fairer assessment of the design space, this is intractable without a detailed dynamic model, and is thus outside the scope of this paper. Additionally, this design study was performed for the case where the palm is most-utilized (hand is placed with the palm facing vertically), but results apply beyond this simple case. The object set consisted of simple geometries with sizes that span typical household objects: three spheres (20, 60, and 100 mm diameters), nine cylinders of varying aspect ratios (3x3 grid of height and diameter with 20, 60, and 100 mm), and nine boxes (3x3 grid of height and width with 20, 60, and 100 mm). All objects had a fixed mass of 50 g, which is similar to many common household objects, such as those found in the YCB object set [19]. The three in-hand manipulation primitives were the same as in [8]: translation and rotation in a plane perpendicular to the palm’s surface. For all experiments, we recorded the 3D pose of the target object, contact points between the hand and object, and the finger actuation signals. The results of these experiments are shown in Figure 4.

In addition to the higher density parameter sweeps in simulation, we validated these results with sparser experiments on physical hardware. We built an array of circular palms with two diameters (70 mm and 85 mm) and two heights (60 mm and 80 mm). All palms were 3D printed on FDM Printers using PLA (using a CR-10s printer, Creality). The palms are interchangeable on the soft hand platform. The object set used consisted of three boxes (23, 30.5, and 61.5 mm in thickness), two cylinders (Cups 1 and 10 from the YCB object set [19], with diameters of 47 mm and 87 mm respectively), and one wooden sphere 63.5 mm in diameter. Using a top-down camera and April Tags [20] to track the object’s pose, we commanded motion primitives using the same heuristic actuation torque trajectories, but converted to actuation pressures for the physical hardware. Actuation pressure signals were generated with a custom real-time pressure controller (same as in [8]). The results of these experiments are shown in Figure 3.

C. *Results of Design Exploration*

The results of our extensive simulated experiments suggest that a single palm height and diameter is not capable of manipulating all object sizes, which is supported by the experiments in real hardware. These findings suggests that a palm that decreases in diameter as a function of height can achieve manipulation performance for all object sizes.

The trends in bulk performance as a function of the palm design and object width appear to match between simulation and real hardware. In Figure 3, the contact success rates and manipulation success rates are shown for both systems as a function of object width. Several key real-world phenomena are preserved in simulation, shown in the callout pictures. For the large, tall palm (85 mm diameter, 80 mm height), we see that small objects cannot be grasped by the fingers, leading to zero success rate. Conversely, larger objects can

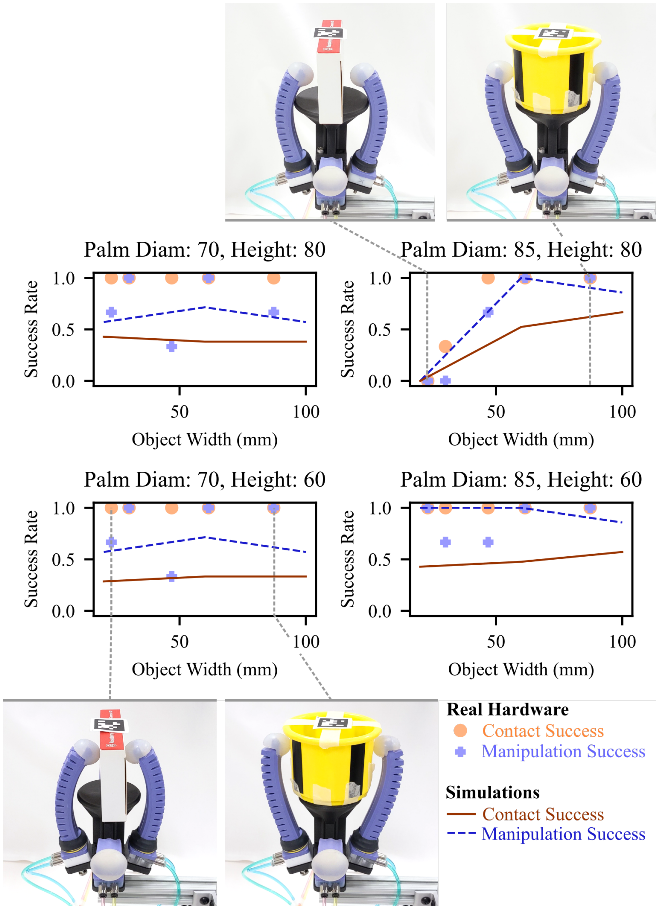

Fig. 3. The main trends in manipulation performance from the simulated sweeps agree with the performance of real hardware. For the tall, large palm (85 mm diameter, 80 mm height), small objects cannot be grasped by the fingers leading to zero success rate, whereas larger objects can be grasped and manipulated with high success. Conversely, for the short, small palm (70 mm diameter, 60 mm height, all object widths can be grasped, but the fingertips touch far from the center of mass. *Each point from real hardware represents the average over the three primitive motions. Each point in simulation represents the average of 21 runs, (three tasks and seven objects), and are shown as lines for graphical clarity.*

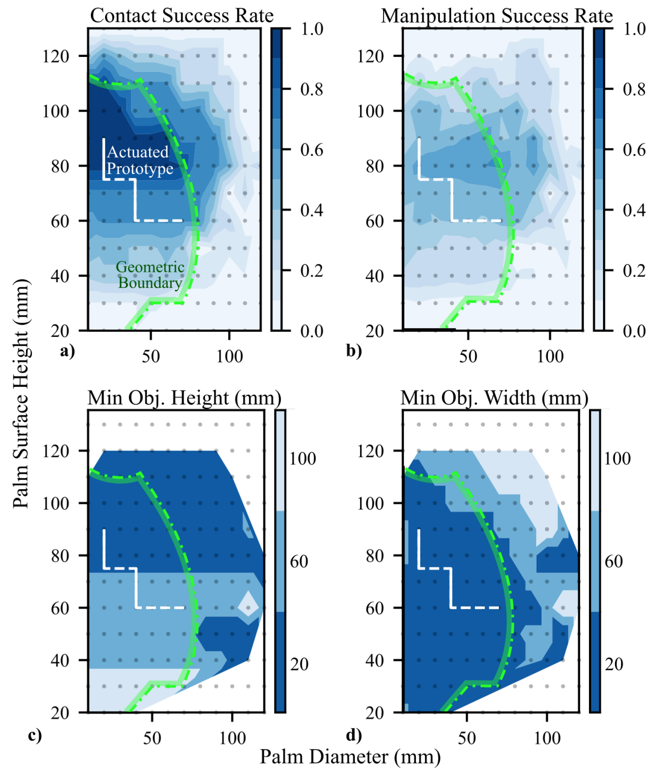

Fig. 4. The palm height and diameter exhibit tradeoffs in grasping and manipulation performance over a variety of objects and manipulation tasks. a) The ratio of trials where the fingers successfully contact the object before manipulating shows a clear maximum near smaller-diameter, taller palms. b) The manipulation success rate reaches a maximum near taller palms of moderate diameter. c) The minimum object heights that were successfully manipulated is dependent only on the palm height and d) the shape of the boundary where the hand successfully manipulates thin objects is similar to the shape of our soft fingers (geometric boundary). Our proposed actuated palm with discrete sections changes diameter as a function of height.

be grasped and manipulated with high success. On the other end of the design spectrum, the short, small palm (70 mm diameter, 60 mm height) could grasp and manipulate all object widths can be grasped with relatively high success (above 50%), but the fingertips touch far from the center of mass of these objects. Simulations were only performed at three object widths (20, 60, and 100 mm) due to the high dimensionality of the sweeps, but the results still agree well with the hardware.

From here, the in-hand manipulation performance of the large-scale simulations over all objects and tasks as a function of the palm design are displayed in Figure 4. Using our performance metrics defined earlier, the results for each palm design (height and diameter) are averaged over all 21 objects and three manipulation tasks. First, Figure 4a shows the ”contact success rate” which describes the ratio of trials where the fingers successfully contact the object at the beginning of the manipulation task. Next, we defined the ”manipulation success rate” as the fraction of runs where the manipulation task is completed without the object falling out of the hand, as shown in Figure 4b. Finally, for all trials that successfully completed 10 task repetitions, the shortest object manipulated at each set of palm parameters is shown in Figure 4c, and the smallest object widths are shown in Figure 4d.

The results illustrate a clear region of design space that produces successful in-hand manipulation. There appears to be a local maximum in contact success rate near palms of smaller diameter, but larger height (near 40 mm diameter, 90 mm height), as indicated in Figure 4a. In addition, Figure 4b clearly shows that manipulation success is relatively high near similar palm heights, but toward the middle of the palm diameter range. However, these first two metrics only tell part of the story. Taking object size into account, we can clearly see that palms with lower heights lose their ability to manipulate short objects, as shown in Figure 4c. On the flip side, thin objects can only be manipulated by smaller, shorter palms as shown in Figure 4d. Furthermore, the shape of the boundary between successful manipulation of thin objects and failure is similar to the shape of our soft fingers when actuated. This makes sense when considering that the source of failures for large-diameter, taller palms is interference

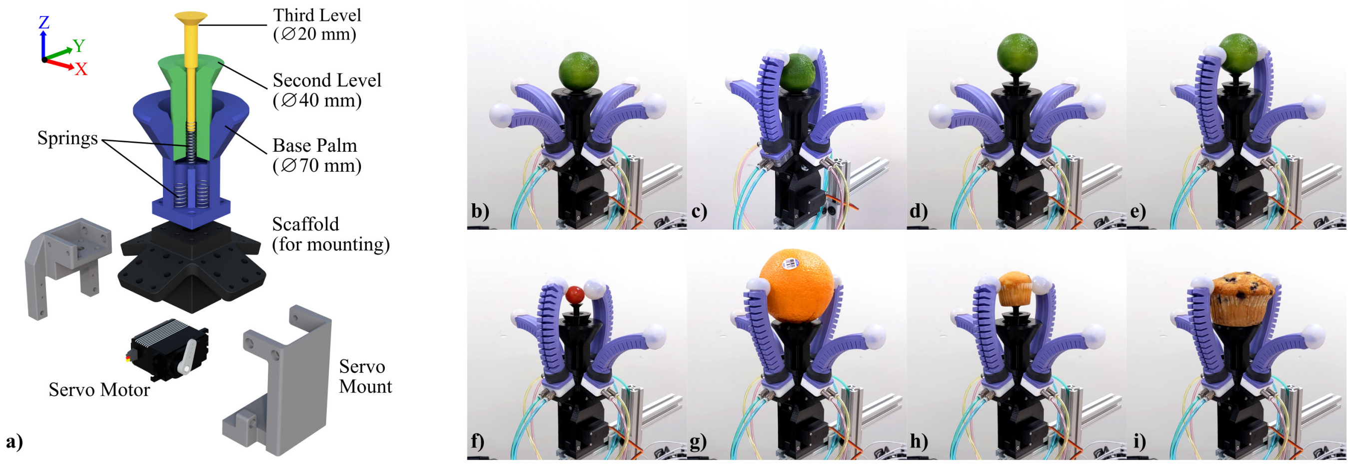

Fig. 5. Our actuated palm design expands the range of object sizes that can be successfully manipulated by controlling the object's vertical position such that the fingertips touch closer to the objects' centers. a) A cut-away view of the actuated palm mechanism shows how the diameter of the surface decreases as a function of height. b-e) The palm can lift smaller-sized objects (such as a lime) into place for the fingers to grasp, and f-i) manipulation tasks can be performed on a variety of object sizes.

between the palm and the fingers.

Based on these results, we can see that no single palm design is capable of highly reliable manipulation for all object sizes, so we propose instead to design an actuated palm capable of adjusting palm height and diameter simultaneously. With one DOF, our proposed palm can transition between a large-diameter, low height palm design, as well as a small-diameter, tall palm. Considering several practical design factors discussed in the next section, we chose to use a discretized approach capable of three different palm diameters which change as a function of height to traverse the design-space, as shown with dotted lines in Figure 4.

IV. Design of the Actuated Palm

Based on the parameter exploration in the previous study, we designed a single palm with one DOF that achieves useful motion perpendicular to the palm's surface, as shown in Figure 1. With a discretized telescoping mechanism in which each palm level has a different diameter-to-height ratio, our palm has the ability to move continuously along the axial direction without causing interference with finger motion. The palm utilizes a rigid mechanism, but is a stepping stone toward our ultimate goal of a soft-bodied palm.

The main constraint informed by our design exploration was determining the maximum palm diameter we could accommodate as a function of the palm's surface height. To make the best use of one additional DOF, the palm diameter should decrease as a function of the palm height to ensure the palm does not interfere with finger motion. This relationship should follow the shape of the geometric boundary of the soft fingers when grasping an extremely thin object.

Our final palm actuation design utilizes a telescoping mechanism to achieve the necessary discretized changes in diameter as a function of the palm's height, as shown in Figure 5a. Only three height levels were chosen for the purpose of demonstrating functionality, and all palm levels were 3D printed on an FDM Printer using PLA (using a CR-10s printer, Creality). The second and third levels are held at their maximum heights by a parallel spring system to isolate their motion, utilizing four springs for the second level to accommodate larger objects with greater mass. To control the height of the palm assembly, a rigid wire connects the third level palm with a servo below. With this one connection, the servo can pull the third level palm down to touch the second level, then continue to pull both the second and third level until they are flush with the base (Figure 5b)

With one degree of freedom, this palm can achieve a spectrum of palm designs through actuation as shown in Figure 5. The dimensions of layers were limited by the mechanism itself, however they fall into a reasonably-successful region. The first level of the palm (base) has a height of 60 mm and diameter of 70 mm. The second and third levels can travel vertically by 15 mm each. The diameter of the third layer was restricted by the size of the fingertips of our soft dexterous hand (20 mm). We chose a diameter of 40 mm for the second level to prevent collisions with the fingers. With these various palm diameters and heights, we can ensure our palm has the largest possible supporting surface at any given height while ensuring no interference with finger motion. While the design is directly tied to the geometry and kinematics of the fingers, we expect this design process to remain valid for a variety of soft finger and hand designs.

V. Results and Discussion

Overall, the actuated palm design translates to real gains in grasping and manipulation performance. With some limited knowledge of the object's dimensions, we can adjust the palm's height to allow manipulation to occur at the fingertips while ensuring no interference with finger motion. When left retracted at a height of 60 mm, the palm supports larger objects (such as the grapefruit or a large muffin in Figure 5) at the same height as the original hand in [8]. With the palm extended to its maximum height (80 mm), it can now support

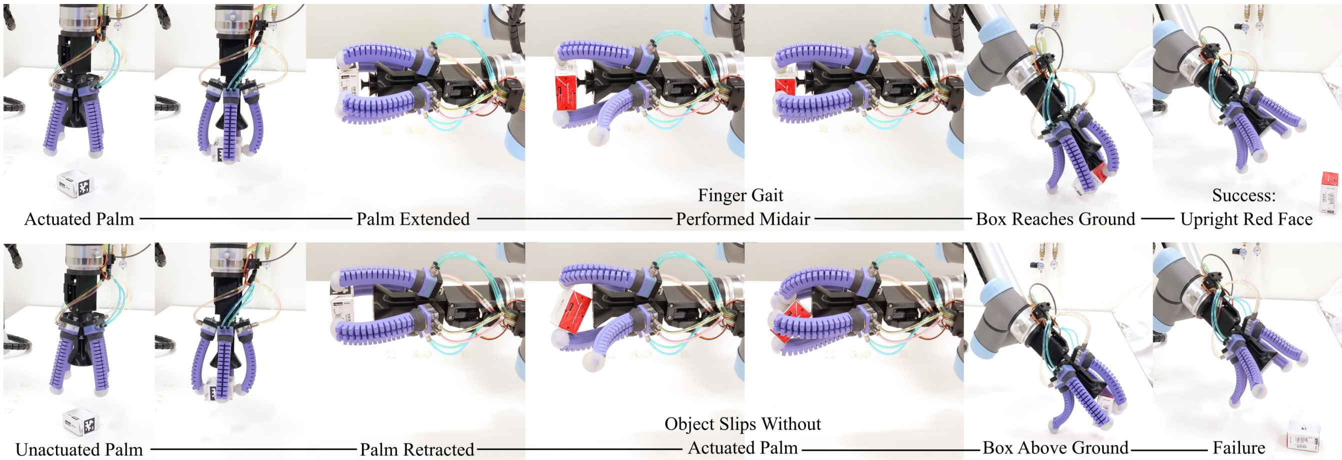

Fig. 6. Having the ability to actuate the palm provides our soft dexterous hand increased stability when grasping smaller objects, which is useful for real-world tasks such as stocking shelves. This is especially evident for in-hand manipulation tasks performed in midair. In this example, the hand rotates the box using a finger gait developed in [8], with the goal of placing a particular face (in red) upright. If the actuated palm extends to support the object (top row), the task is completed successfully. However, if the palm is not extended (bottom row), the object slips sideways, and ultimately the task fails.

smaller objects such as a grape or small muffin. Furthermore, we can clearly see the benefit of the actuated palm's ability to adjust the height of the object on-the-fly to support small objects (such as a lime in Figure 5b-e) at the correct height to be manipulated by the fingertips.

To demonstrate the benefits provided by our actuated palm in a more-realistic task, we set up a manipulation task derived from the application of stocking shelves. A common task in shelf stocking involves placing items in a specific orientation that displays graphics towards the customer. Using a UR5e (Universal Robots) 6-DOF robot arm we performed a similar task manipulating the object within the hand in midair with the support of our actuated palm, as shown in Figure 6.

The goal of the manipulation task is to pick up a short square pneumatic fittings box (Parker), and rotate it such that the red side faces upwards when placed on the table. This box does not touch the retracted palm when picked up from the table. Next, two gait cycles of a finger gait for continuous rotation are executed by the hand. The gait compensates for the weight of the object and fingers (see [8]), but no other tuning is required. If the palm remains retracted, the finger gait fails, resulting in undesired motion of the box. Thus, when the robot attempts to place the box on the table, it drops the box instead. Alternatively, if the palm extends (increases in height) before the rotation begins, the box's motion during manipulation is constrained by contact with the palm. This results in predictable object motion, which ultimately enables the robot to successfully place the box on the table with the correct side up.

VI. Conclusion

In summary, we demonstrated an active palm that can change its height and diameter to enable high-quality in-hand manipulation for a large range of object sizes. The actuated palm provides stabilizing contact to objects, and helps control the axial position of objects with respect to the fingertips. We leveraged a combination of physical and virtual experiments to explore the effects of the palm's design space on in-hand manipulation performance. The results of these experiments indicate that the palm's diameter must decrease as a function of its height to ensure finger motion is not impeded. Using these results, we designed an actuated palm mechanism that controls the palm height and diameter relationship using one actuated degree of freedom. We demonstrate that the actuated palm enables successful manipulation of larger range of object widths and heights. Finally, the actuated palm enables the hand to perform a complex in-hand manipulation task in mid-air.

In future work, we expect that studying the role of the palm in soft manipulation could yield a plethora of opportunities to improve the design and performance of soft hands. Expanding the palm's design space to include more physical properties such as surface concavity, friction, and compliance could lead to insights about suitable fully soft palm designs. Further investigating palm design for hands with different finger arrangements, such as anthropomorphic, could also yield an understanding of the palm's role more-generally in grasping and manipulation. Finally, an actuated palm such as the one proposed in this study could enable soft robotic hands to perform complex in-hand manipulation tasks in the real-world, such as activities of daily living in the home, using hand tools, or stocking display shelves.

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