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Multiplexed Manipulation:
Versatile Multimodal Grasping via a Hybrid Soft Gripper

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***Abstract*— The success of hybrid suction + parallel-jaw grippers in the Amazon Robotics/Picking Challenge have demonstrated the effectiveness of multimodal grasping approaches. However, existing multimodal grippers combine grasping modes in isolation and do not incorporate the benefits of compliance found in soft robotic manipulators. In this paper, we present a gripper that integrates three modes of grasping: suction, parallel jaw, and soft fingers. Using complaint handed shearing auxetics actuators as the foundation, this gripper is able to multiplex manipulation by creating unique grasping primitives through permutations of these grasping techniques. This gripper is able to grasp 88% of tested objects, 14% of which could only be grasped using a combination of grasping modes. The gripper is also able to perform in-hand object re-orientation of flat objects without the need for pre-grasp manipulation.**

I. INTRODUCTION

Reliable grasping and dexterous manipulation remains one of the largest open problems of robotics. It is extremely difficult for a manipulator with a single grasping technique to handle the sheer variety of objects' geometries, material properties and poses required for robots to be useful in dynamic real world environments. Part of the difficulty lies in the end-effector design. Despite significant advances in manipulator design — especially in underactuated, soft robotic, and anthropomorphic designs [1–3] — the complexity of these manipulators make them bulky, expensive, and not robust [4]. Thus, the majority of industrial grippers are either suction or parallel jaw grippers, whose simplicity and precision outweighs the cost of more complex control [5].

Given the success of suction-based approaches in the 2015–2017 Amazon Picking/Robotics Challenges, robotics researchers have become more open to combining multiple grasping modalities. About half of all teams in the 2015 Amazon Picking Challenge reported that they wished they had incorporated suction in their design [6]. This desire for multimodal grasping was borne out in subsequent Amazon Robotics Challenges, where all of the top placing teams used a combination of suction and parallel jaw approaches [7–10]. Combining suction's ability for single-point grasping and parallel jaw's caging grasp can allow for a greater variety of objects to be manipulated [11].

Although multimodal grasping has been recognized as an important way to improve manipulation, integration of these modes remain limited. Current grasp planning research treats parallel jaw and suction grasping modes as completely separate forms, exemplified by the two arm "ambidextrous" approach shown in [12]. To achieve true multimodal grasping capabilities, we need to move away from binary and sequential selection of grasping modalities and towards a combinatorial approach.

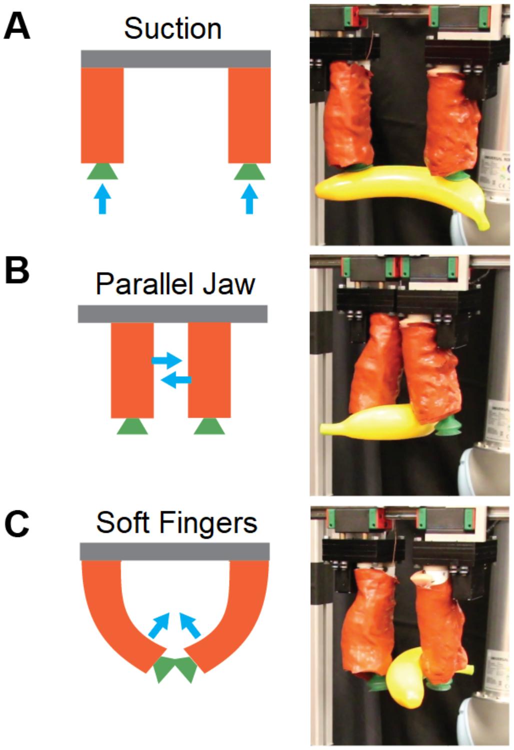

Fig. 1. Schematic and pictures of the gripper's multiple modes of grasping, demonstrating (A) suction, (B) parallel jaw grasping, and (C) soft finger grasping

To address this need, we present a gripper which combines three different grasping modalities — suction, parallel jaw, and soft finger — into one package(Fig. 1). We are able to efficiently grasp around an object with soft bending fingers using shearing auxetic actuators, apply a rigid clamping force with a parallel jaw style grasp or accurately place suction cups on an object's surface. This system not only allows us to use each of these methods independently, but also allows us to have these grasping modalities work in a multiplexed fashion. Combining multiple grasping modes creates a higher object holding force and allows us to perform in-hand manipulation — changing a plate's orientation from horizontal to vertical. In grasping tests, our multiplexed manipulator could pick up 88% of our tested objects, 14% of

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which could *only* be picked up by a combination of grasping modes.

In this paper, we

- design and characterize a new gripper which seamlessly integrates three modes of grasping: suction, parallel jaw and soft fingers
- show the versatility of this gripper by performing a thorough categorization of objects and their graspability for each mode
- demonstrate basic in-hand manipulation by multiplexing different grasping modalities to put away dishes

II. RELATED WORK

Most of the current hybrid / multimodal gripper designs were created in response to the success of suction in the Amazon Picking/Robotics Challenge. The simplest are the binary selection grippers. These grippers focus on simply delivering either the suction mode or the parallel jaw mode to the object as easily as possible, and so keep the two end-effector types largely disjoint. We can see this in the design of the 2017 overall winning robot Cartman and the 2017 stow task winning robot from MIT; both of these robots used a tool change mechanism to switch between suction and parallel jaws [9, 13]. Some teams went even further with this separation between grasping modes, using an off-the-shelf gripper to grasp a suction tool or having two arms, each with their own end-effector [6, 11].

Recent gripper designs have combined suction and grasping into a unified end-effector to enable sequential operation. These designs tend to place the suction at the tip of existing fingers or palms to supplement standard grasping capabilities. These finger bases can vary from tendon-driven systems [14], a simple two finger grasping system [10], or as an extra point of stabilization over two movable rods [15]. Industry has embraced this combination of compliant grippers with suction as the main solution for each-picking operations. RightHand Robotics, Soft Robotics, and Kindred all use suction followed by compliant gripping to perform piece picking operations. They rely on suction as the primary gripping modality and use complaint grasping to prevent shear and to recover from suction failure. This prioritization of suction limits their applicability beyond the objects with flat faces found in industrial warehouse automation environments.

Fully integrated designs highlight the potential benefits for combining the suction and parallel jaw modalities more tightly, allowing for greater flexibility on grasping and manipulating objects. In particular, the iGRIPP 4 was able to combine suction and parallel grasps into an articulated Barrett-style hand, allowing it to pick up small thin objects and put things in envelopes [16]. However, none of these fully-integrated grippers combine suction or the material-based compliance found in soft robot manipulators [17].

III. GRIPPER DESIGN AND FABRICATION

Our design goals for this gripper were to incorporate three different grasping modalities (suction, parallel jaw, and soft fingers) into a single package, where each mode can be performed individually or in conjunction with the other modes. Just as multiple signals can be multiplexed into a single signal, so too did we want these multiple forms of grasping modalities to be multiplexed into a single coherent form of manipulation. We also wanted to be conscientious of the size of the gripper, as bulk and complexity have been noted as reasons that more effective grippers have not been adopted over suction or the parallel-jaw gripper [5].

To achieve these goals, we built our gripper primarily around handed shearing auxetic (HSA) actuators. HSAs provide a material foundation to create compliant electrically-driven actuators, giving us the benefits of soft robotics without needing the typical complex driving hardware [18]. Depending on how we drive the HSAs, we can change the stiffness of the fingers, allowing us to more easily recreate the typical suction and parallel-jaw grasping modalities.

We use a pair of HSA cylinders for each finger of our gripper to allow for soft grasping. Each of these fingers has a suction cup at the tip, and are connected to a belt drive to allow for parallel-jaw grasping. An overview of the mechanical design can be seen in Fig. 2A. The entire system was fabricated out of waterjet aluminum, mounted to a Universal Robotics UR-5 robot and controlled via ROS and an Arduino. In total, the on-board weight of the gripper is 0.8 kg with a grasping volume of 11.5 x 11.5 cm.

A. Soft Grasping

The core of this gripper is around its fingers, which are built from HSA-based actuators. HSAs are a new material class which expand on the concept of traditional auxetics — materials with a negative Poisson's ratio that expand in width when pulled in length. When pulled laterally, HSAs expand with a net shear and a specific chirality, meaning that twisting a HSA will also create linear extension [19]. If two HSA cylinders of opposite handedness are paired and counterrotated against one another, they will act as a unit by opposing one another's desire to rotate and maintaining a linear extension. Adding an internal constraint layer to the geometric pattern can force this unit to bend out of plane rather than simply extend linearly [18]

Since we can directly drive HSAs with a motor, this makes them the perfect actuator fit for our gripper. A compliant gripper can be achieved with minimal driving hardware, while the hollowness of the HSAs allows us to easily incorporate the suction grasping mode with the fingers.

Each HSA cylinder was made by laser cutting a 90 mm long, 25.6 mm diameter, 1.58 mm wall thickness PTFE tube on a rotary engraver (PLS6.150D, Universal Laser Systems). We laser cut the pattern from [20], namely, a constrained bending design with 2222 symmetry, with six repeated base units around the cylinder's circumference.

Each finger of our gripper was made of a pair of HSA cylinder, making each finger about 55 mm wide and 90 mm long. The HSA pair was driven by a Hitec HS-5585MH servo, with counter-rotation provided by gears. A simple gear box was created by stacking laser cut acrylic plates. In order to increase grasp friction, a foam insert was attached via

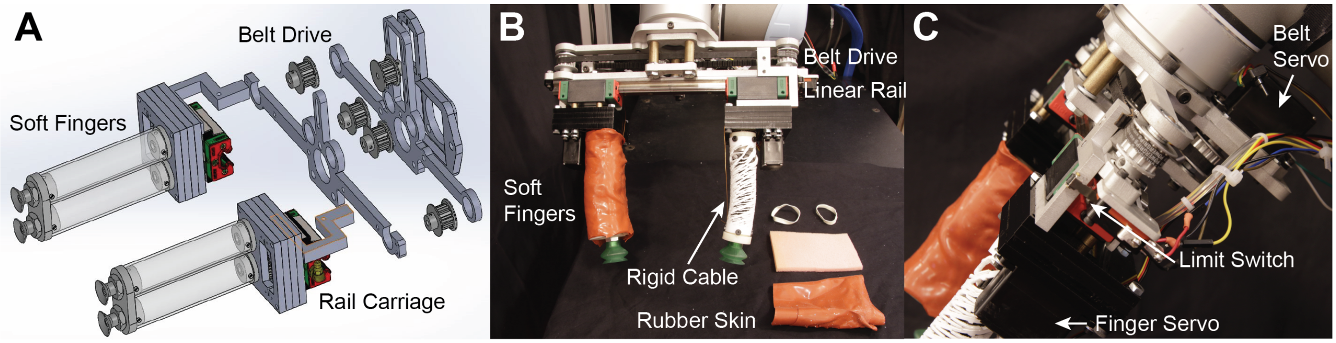

Fig. 2. Gripper design schematics. (A) Design drawing illustrating the belt drive of the soft finger platforms on a linear bearing. (B) Front view of the gripper, with rubber covering on and off, showing limit switch wire. (C) Side view of the gripper, highlighting the belt system

rubber bands to the PTFE cylinders, which was then covered by an open-ended rubber sock (Fig. 2B). Furthermore, to increase cylinder stiffness in shear and torsion, rigid cable guards are added inside each of the cylinders.

B. Parallel Grasping

In order to get a parallel grasp, we need to drive each of the HSA fingers linearly together and apart. To do this, we treat each finger as a stage on a linear rail, driving the motion via a belt drive (Fig. 2C).

Each finger unit was mounted onto a HGH15CA linear stage, which clamped onto the timing belt via a custom waterjet part. A continuous Hitec HS-5585MH servo in the back drives the belt, allowing the gap between fingers to vary from 0 mm to 120 mm. Since the continuous servo has no feedback, limit switches are added to the ends of the linear rail to tell the servo when to stop. A wire connecting to a limit switch is also placed along each of the fingers' inner curves to try to prevent the parallel grasp from crushing any objects (as seen in the right finger in Fig. 2B).

C. Suction

To integrate suction, we drew inspiration from existing hybrid grippers and placed suction cups at the tip of our fingers. The hollow nature of the HSA cylinders made it easy to lay tubing through the fingers and exit each of the finger stages. Although there was space for two suction cups per finger, we chose to only use one to minimize complications in tubing routing. Once installed in the 3D-printed finger cap, replacing a suction cup design was as easy as loosening a nut. For our experiments, we chose the Schmalz bellows suction cup (10.01.06.03494) due to its compact size and being specifically designed for uneven surfaces.

Rather than use a large vacuum pump, we instead chose to power each finger with a Parker C103E-12 pump. Although these pumps have a lower flow rate than typical vacuum pumps (5 L / min at 27 kPa), we chose these pumps for their small size, so if necessary, they could be mounted to the arm or hand for mobile robotic applications.

D. Grasp Mode Definitions

Before we can fully understand the effects of multiplexing grasping modalities, we need to first understand each of the grasping modes in isolation first. To help ensure consistency, we define our grasping modes as follows:

1) a **suction grasp attempt** occurs when (a) the fingers are manually driven together by the belt drive until the suction cups are over the graspable area, and (b) the arm moves down onto an object, making full surface contact between the suction cups and the object
2) a **parallel grasp attempt** occurs when the fingers are driven together by the belt drive until the limit switch triggers
3) a **soft finger grasp attempt** occurs when (a) the fingers are manually driven together by the belt drive until the fingers are almost touching the object but no lateral force is applied, and (b) the fingers are driven by the finger-specific servos to bend in onto the object

Thus, when we say that we "multiplex" these modes, we mean that we deviate from these standard attempt definitions by combining elements from each group. For example, multiplexing parallel and soft grasps may mean that we perform a parallel grasp attempt and then perform a soft grasp attempt, allowing the fingers to curl around the object after a strong lateral force is applied.

IV. GRIPPER CHARACTERIZATION AND DEMONSTRATION

A. Grasping Force Characterization

We characterize our gripper by investigating two classes of forces: (1) the lateral forces experienced when an object is pressed by the gripper, and (2) the maximum amount of force the gripper can exert to hold an object in place. Since using the suction mode alone does not involve any finger contact, we only provide a characterization of the peak holding force for that mode.

To characterize the first class of forces, we need to measure the lateral grasping forces in situ. We do so by holding a digital scale at different depths of the grasp volume and performing either a parallel jaw grasp or a soft finger

TABLE I
AVERAGE PRESSING FORCE OF GRASPING MODES

Grasping Mode	Location	Force (N)
Suction	Tip (1 cup)	23.9 ± 0.6
Soft	Full finger	0.75 ± 0.1
Parallel	Tip	0.73 ± 0.2
	Halfway	2.31 ±0.3
	Full finger	11.1 ±0.33
	Full finger + stage	15.7 ±0.8

grasp. For each location, five force measurements were taken and averaged, as summarized in Tab. I.

To characterize the second set of forces, we have two procedures. For the parallel and soft finger grasps, we set the gripper in a materials testing machine (Instron 5544A) and have it grip a 3D printed test objects with diameter 60 mm (cylinder, sphere and stepped stage). We then perform an extension test, stopping when the object slips out of the manipulator's grasp (Fig. 3). For the suction grasp, we grasp a scale that is held flat against the table and record the maximum force reported before the suction cups pop off. These suction results are reported in Tab. I for cleanliness.

We see that the suction grasping mode is by far the most powerful grasping mode (one cup exerts 23.9 ± 0.6 N), while the soft grasping mode is the weakest (0.75 ± 0.1 N with the scale placed along the full finger length). Combined with the fact that this soft grasping reading matches the tip-only pressing force for the parallel grasp (0.73 ± 0.2 N), we see that this force measurement is consistent with soft manipulators. The inherent compliance of the fingers causes the soft finger grasp to only exert the force needed to just hold the object in place, making it difficult to precisely quantify the maximum pressing force any object can receive from a soft grasp. Indeed, this discrepancy is highlighted by the peak holding force recorded for the soft grasp ($\approx 7.8 - -10.7$ N) being one order of magnitude larger than the recorded pressing force.

Despite this small magnitude, we know that the soft grasp *does* have an effect, given that the peak holding forces for the multiplexed parallel + soft grasping result in significantly different values from parallel grasping alone, especially for the sphere (37.9 ± 2 N vs. 27.5 ± 0.7 N). This difference demonstrates that having the soft fingers able to curl around an object can sometimes result in a more secure hold — although not in the case of the stepped stage which showed a drop in holding force from 36.8 ± 1.5 N to 32.0 ± 1.3 N. This drop in force may be due to the soft bending changing where the stage presses into the parallel grasp. As Tab. I shows, the parallel grasping force can change dramatically depending on how much contact the object has with the finger. The closer the scale goes to the rigid components at the base of the fingers, the greater the force output, resulting in non-linear jumps in grasping force as the halfway point has over three times the grasping force as at the tip (2.31 ± 0.3 N vs. 0.73 ± 0.2 N). Thus, depending on how the soft fingers bend around the stepped stage, the point where parallel grasping kicks in may be non-ideal for a tight grasp.

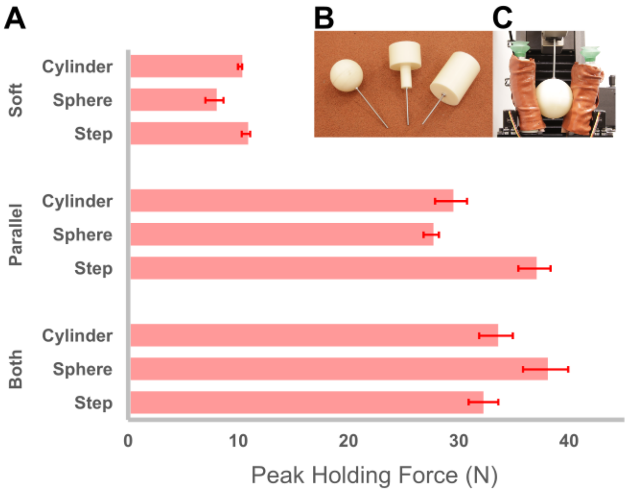

Fig. 3. (A) Peak holding force for different grasp modalities. Note how combining soft and parallel grasping techniques results in a higher holding force for all of the objects. (B) Objects used in testing. (C) Image of the Instron testing setup.

B. Grasping Tests

To evaluate the benefits of our combinatorial approach for robust grasping, we conduct grasping tests on as wide a range of items as we can find. We grasped 75 objects, 29 of which came from the YCB dataset, a standardized benchmark for manipulation ability [21]. A wide range of form factors and material properties were chosen to test the versatility of our gripper.

Since we were only interested in the mechanical performance of the gripper, no motion planning was used. Instead, all objects were manually placed within the gripper's available area. However, for added realism, all objects were placed flat on the table surface and were not elevated for optimal positioning.

For each object, the gripper would come down to a preset location, perform a grasp attempt and attempt to lift the object. A grasp was considered successful if the object could be lifted without falling. Single-mode grasping attempts were performed as defined in Sec. III-D, while all multiplexed grasping attempts were manually controlled using the existing primitives. If the object was able to be grasped by a solo mode, it was assumed that any multiplexed manipulation that included that modality would be successful. The results of these tests and a list of all objects used are summarized in Tab. II, while pictures of all of these objects can be found in Fig. 4 and 5.

Overall, the multiplexed manipulator was very successful in grasping a wide range of objects, grasping 88% of all objects and 90% of all YCB objects. The objects that weren't able to be grasped were mainly due to weight (dumbbell,

TABLE II

RESULTS OF GRASPING TESTS ACROSS MODES

	Total Items	Graspable	Suction Only	Parallel Only	Auxetic Only	Suction + Parallel	Parallel + Auxetic	Auxetic + Suction
All Objects[a]	75	66 88%	26 35%	54 72%	53 71%	57 76%	65 86%	56 75%
YCB Objects[b]	29	26 90%	12 41%	24 83%	23 79%	24 83%	26 90%	24 83%

[a] **Graspable by All Modes:** Tea can, Toy street sign, Plastic shoe, Screen wipe, Coffee can*, Modeling clay (ball), 4" cardboard box, Milk carton, Large lego, Mouse, Mentos container, Paper cup, Fake banana*, Pringles*, Tuna can*, Fake apple*, Mug*, Spatula*, Pitcher*, Jello*, Fake Orange*, Fake lemon* **Graspable by All but Suction:** Foam block*, Green tape, Egg beater, Brush, Dragon, Cloth (crumpled)*, Rubber duck, 3d printed plug, PVC tape, Double sided tape, Soda bottle, 4" hollow metal ball, Plastic bag (crumpled), Football, Eightball, Arduino, Sponge, Metal C, Baseball*, Fake pear*, Fake peach*, Clamp*, Softball*, Tennis ball*, Raquetball*, Fake plum*, Fake strawberry* **Graspable by All but Soft:** Bucket, Windex* **Graspable by All but Parallel:** Squeegee, Xbox controller **Graspable Only by Parallel:** Modeling clay (flat), Plastic bag (flat), Fake chains* **Graspable Only by Soft:** Rolling pin, Screwdriver* **Graspable Only by Multiplexing:** Wire strippers, Guinea pig, Hinge, Toilet brush, USB, Keyboard, 4x4 block*, Neoprene Foam **Not Graspable:** Scissors*, Dumbbell, 1 kg weight, Cloth (flat)*, Rubber band, Metal rod, Pen, Shoe, Fat expo*

[b] Asterisks denote YCB objects, a dataset from [21]

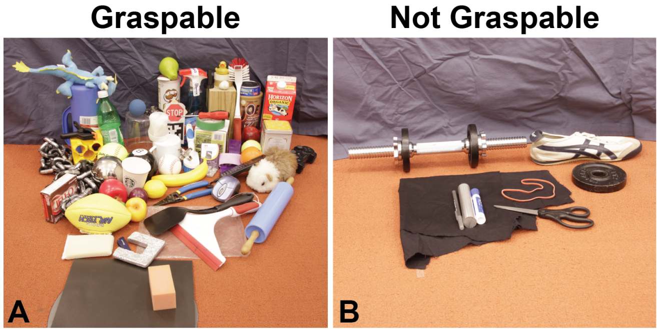

Fig. 4. Image of all objects used in testing. (A) Objects that were capable of being grasped by at least one modality. (B) Objects that could not be grasped at all by our gripper. These objects tended to be heavy, have a low profile, and lacked a smooth flat surface.

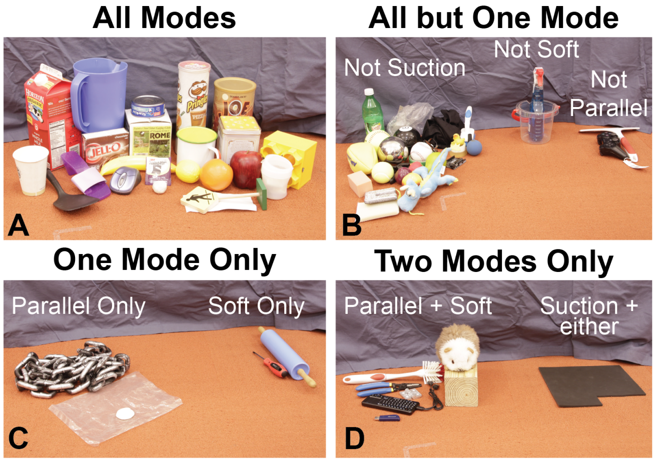

Fig. 5. Subdivision of all graspable objects by which modalities could grasp them. (A) Objects that could be grapsed by all modes. These tended to be larger or have one smooth flat surface. (B) Objects that could be grasped by all but one mode. Suction notably had significant difficulty with curved objects and rough surfaces. (C) Objects that could be grasped by only one mode. (D) Objects that could only be grabbed by a combination of grasping modes.

flat cloth, metal rod) — which would push the HSA-based fingers out of the way — or their low profile (shoe, expo, pen, freeweight, scissors, rubber band), which made it difficult for the fingers to properly curl/cage around the object. All of these objects also had a rough or curved surface, making it difficult for the suction cups to get a sufficient grip.

Among the graspable objects, clear trends began to emerge for each grasping modality. Despite having the strongest grasping force, suction proved to be the worst performing grasping modality. This is largely due to its heavy dependence on surface quality and material property, making it unable to grasp many round, porous and soft objects (Fig. 5B). Meanwhile, parallel grasping was significantly better at grabbing straight-walled objects (windex, bucket, chains), as these straight walls meant more surface area contact between pressed fingers. Soft grasping could better handle long irregular shaped objects (squeegee, rolling pin) as there was more space for the fingers to curl and support these objects.

Perhaps most interesting are the objects that could *only* be grasped with a combination of grasping modes (Fig. 5D). The combination of parallel and soft grasping modalities allowed simultaneously more finger area contact and the ability to better curl under objects, especially by using the suction cup as a pseudo-fingernail. This combined modality allowed for better grasping of heavier objects (wood block) and objects with low clearance (guinea pig, keyboard, usb), to dig under low profile objects. These are notably also a similar category of objects as the ungraspable items in Fig. 4B, suggesting further potential for this multiplexed manipulation strategy.

Multiplexing suction with either parallel or soft grasping modalities helped pick up a similar low profile object – neoprene foam. Although the foam was too porous for the suction to pick up by itself, the suction cups provided a sufficient pivot point for the parallel and soft grasping modes to create a fold in the material, which could then be used to grasp the entire material.

V. IN-HAND MANIPULATION

As a demonstration of other manipulation capabilities beyond simple grasping, we demonstrate in-hand orientation change by multiplexing our different modes of grasping. As seen in Fig. 6, the integrated design of our manipulator allows us to pick up a flat object straight from a table and then reorient it into a traditional parallel jaw grasp. We can do this movement without having to rely on pre-grasping manipulation, such as sliding the object to the edge of the table or precisely placing the manipulator around the object to create a flipping motion [22, 23].

Our algorithm is general beyond just flat objects and will work as long as there is a single point of contact where the suction can grasp (Algo. 1). It also allows us to pick up objects that are too large to be caged by the parallel / soft finger grasps if picked up straight from a flat surface.

Although we were able to successfully manipulate plates and CDs, we had difficulty with heavier objects like books and magazines. The weight of these larger objects caused the compliant HSA fingers to not curve upwards as much, making it harder for the soft fingers to curl under the suctioned object as desired. We did note that the fingers did curve enough to possibly attach to the spine of the book, especially if the suction cup were angled more from the tip. Further experiments with tip design or increased torque on the HSA fingers could potentially resolve these issues.

Algorithm 1: Orientation-Flipping Algorithm

```
Apply suction;
Move down to object and grasp with suction force;
Lift hand + object;
Close parallel until closing soft fingers is around object;
while Parallel limit switch not activated do
    Turn off suction;
    Move parallel grasp inwards;
end
```

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we have demonstrated a gripper that can multiplex three different grasping modalities into one coherent package. This gripper allows us to not only access the benefits of each grasping mode, but also multiplex these approaches and manipulate objects that no one grasping mode can do alone. Out of 75 objects, 88% can be grasped, 14% of which could only be grasped by a combination of modes. We also demonstrated that multiplexed manipulation allows us to engage in in-hand object re-orientation, hinting at a much larger available space of grasp primitives.

Future work on this system will work on incorporating advances in multimodal grasping for this multiplexed approach. Dexnet 4.0 and other multimodal grasp planning techniques have shown great promise; extending these ambidextrous learning policies to handle more complex grasp primitives will enable more sophisticated manipulation [12].

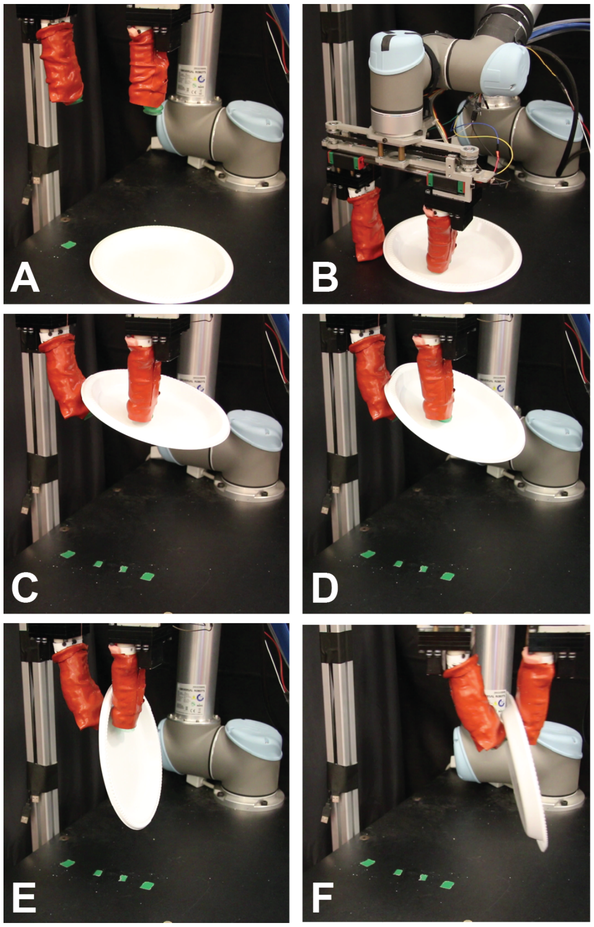

Fig. 6. In-hand manipulation between grasping modalities to change an object's orientation. (A) Given a paper plate, (B) the robot arm comes down and applies a suction. (C) The arm then moves up, bringing the plate with it. (D) The soft fingers curl around the plate, creating a firmer grasp. (E) Suction is released while the parallel mechanism closes simultaneously, (F) providing a sufficient grip for further transport.

In addition, there are still many physical design changes that could be implemented to improve performance. In particular, increasing the stiffness and grasping force capability of the soft HSA fingers would help expand the re-orientation capabilities by giving more specific control of the finger positions. Emphasizing the "fingernail" role of the suction cups could also help in more precision manipulation. Whether it's angling the suction cups or adding an explicit spatula component, having a way to slightly elevate the object from the surface could make more objects graspable.

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REFERENCES

[1] L. U. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, "A compliant, underactuated hand for robust manipulation," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, Apr. 2014.

[2] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, "Soft Robotics for Chemists," *Angewandte Chemie*, vol. 123, no. 8, pp. 1930–1935, Feb. 2011.

[3] OpenAI, M. Andrychowicz, B. Baker, M. Chociej, R. Jozefowicz, B. McGrew, J. Pachocki, A. Petron, M. Plappert, G. Powell, A. Ray, J. Schneider, S. Sidor, J. Tobin, P. Welinder, L. Weng, and W. Zaremba, "Learning Dexterous In-Hand Manipulation," *arXiv:1808.00177 [cs, stat]*, Aug. 2018.

[4] K. Yamaguchi, Y. Hirata, and K. Kosuge, "Underactuated robot hand for dual-arm manipulation," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept. 2015, pp. 2937–2942.

[5] M. Guo, D. V. Gealy, J. Liang, J. Mahler, A. Goncalves, S. McKinley, J. A. Ojea, and K. Goldberg, "Design of parallel-jaw gripper tip surfaces for robust grasping," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, May 2017, pp. 2831–2838.

[6] N. Correll, K. E. Bekris, D. Berenson, O. Brock, A. Causo, K. Hauser, K. Okada, A. Rodriguez, J. M. Romano, and P. R. Wurman, "Analysis and Observations From the First Amazon Picking Challenge," *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 1, pp. 172–188, Jan. 2018.

[7] C. Hernandez, M. Bharatheesha, W. Ko, H. Gaiser, J. Tan, K. van Deurzen, M. de Vries, B. Van Mil, J. van Egmond, R. Burger, M. Morariu, J. Ju, X. Gerrmann, R. Ensing, J. Van Frankenhuyzen, and M. Wisse, "Team Delft's Robot Winner of the Amazon Picking Challenge 2016," in *RoboCup 2016: Robot World Cup XX*, ser. Lecture Notes in Computer Science, S. Behnke, R. Sheh, S. Sarıel, and D. D. Lee, Eds. Springer International Publishing, 2017, pp. 613–624.

[8] D. Morrison, A. W. Tow, M. McTaggart, R. Smith, N. Kelly-Boxall, S. Wade-McCue, J. Erskine, R. Grinover, A. Gurman, T. Hunn, D. Lee, A. Milan, T. Pham, G. Rallos, A. Razjigaev, T. Rowntree, K. Vijay, Z. Zhuang, C. Lehnert, I. Reid, P. Corke, and J. Leitner, "Cartman: The Low-Cost Cartesian Manipulator that Won the Amazon Robotics Challenge," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, May 2018, pp. 7757–7764.

[9] A. Zeng, S. Song, K.-T. Yu, E. Donlon, F. R. Hogan, M. Bauza, D. Ma, O. Taylor, M. Liu, E. Romo, N. Fazeli, F. Alet, N. Chavan Dafle, R. Holladay, I. Morona, P. Q. Nair, D. Green, I. Taylor, W. Liu, T. Funkhouser, and A. Rodriguez, "Robotic pick-and-place of novel objects in clutter with multi-affordance grasping and cross-domain image matching," *The International Journal of Robotics Research*, p. 027836491986801, Aug. 2019.

[10] M. Schwarz, C. Lenz, G. M. García, S. Koo, A. S. Periyasamy, M. Schreiber, and S. Behnke, "Fast Object Learning and Dual-arm Coordination for Cluttered Stowing, Picking, and Packing," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, May 2018, pp. 3347–3354.

[11] Z. Littlefield, Shaojun Zhu, H. Kourtev, Z. Psarakis, R. Shome, A. Kimmel, A. Dobson, A. F. De Souza, and K. E. Bekris, "Evaluating end-effector modalities for warehouse picking: A vacuum gripper vs a 3-finger underactuated hand," in *2016 IEEE International Conference on Automation Science and Engineering (CASE)*. Fort Worth, TX, USA: IEEE, Aug. 2016, pp. 1190–1195.

[12] J. Mahler, M. Matl, V. Satish, M. Danielczuk, B. DeRose, S. McKinley, and K. Goldberg, "Learning ambidextrous robot grasping policies," *Science Robotics*, vol. 4, no. 26, p. eaau4984, Jan. 2019.

[13] S. Wade-McCue, N. Kelly-Boxall, M. McTaggart, D. Morrison, A. W. Tow, J. Erskine, R. Grinover, A. Gurman, T. Hunn, D. Lee, A. Milan, T. Pham, G. Rallos, A. Razjigaev, T. Rowntree, R. Smith, K. Vijay, Z. Zhuang, C. Lehnert, I. Reid, P. Corke, and J. Leitner, "Design of a Multi-Modal End-Effector and Grasping System: How Integrated Design helped win the Amazon Robotics Challenge," *arXiv:1710.01439 [cs]*, Oct. 2017.

[14] S. Hasegawa, K. Wada, Y. Niitani, K. Okada, and M. Inaba, "A three-fingered hand with a suction gripping system for picking various objects in cluttered narrow space," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept. 2017, pp. 1164–1171.

[15] H. Zhu, Y. Y. Kok, A. Causo, K. J. Chee, Y. Zou, S. O. K. Al-Jufry, C. Liang, I. Chen, C. C. Cheah, and K. H. Low, "Strategy-based robotic item picking from shelves," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2016, pp. 2263–2270.

[16] K. Yamaguchi, Y. Hirata, and K. Kosuge, "Development of robot hand with suction mechanism for robust and dexterous grasping," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Nov. 2013, pp. 5500–5505.

[17] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendo, and F. Iida, "Soft Manipulators and Grippers: A Review," *Frontiers in Robotics and AI*, vol. 3, Nov. 2016.

[18] L. Chin, J. Lipton, R. MacCurdy, J. Romanishin, C. Sharma, and D. Rus, "Compliant electric actuators based on handed shearing auxetics," in *2018 IEEE International Conference on Soft Robotics (RoboSoft)*. Livorno: IEEE, Apr. 2018, pp. 100–107.

[19] J. I. Lipton, R. MacCurdy, Z. Manchester, L. Chin, D. Cellucci, and D. Rus, "Handedness in shearing auxetics creates rigid and compliant structures," *Science*, vol. 360, no. 6389, pp. 632–635, May 2018.

[20] L. Chin, M. C. Yuen, J. Lipton, L. H. Trueba, R. Kramer-Bottiglio, and D. Rus, "A Simple Electric Soft Robotic Gripper with High-Deformation Haptic Feedback," in *2019 International Conference on Robotics and Automation (ICRA)*. Montreal, QC, Canada: IEEE, May 2019, pp. 2765–2771.

[21] B. Calli, A. Walsman, A. Singh, S. Srinivasa, P. Abbeel, and A. M. Dollar, "Benchmarking in manipulation research: Using the yale-cmu-berkeley object and model set," *IEEE Robotics & Automation Magazine*, vol. 22, no. 3, pp. 36–52, 2015.

[22] K. Hang, A. S. Morgan, and A. M. Dollar, "Pre-Grasp Sliding Manipulation of Thin Objects Using Soft, Compliant, or Underactuated Hands," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 662–669, Apr. 2019.

[23] L. U. Odhner, R. R. Ma, and A. M. Dollar, "Precision grasping and manipulation of small objects from flat surfaces using underactuated fingers," in *2012 IEEE International Conference on Robotics and Automation*. St Paul, MN, USA: IEEE, May 2012, pp. 2830–2835.