**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

# GRASP: Grocery Robot's Adhesion and Suction Picker

Amar Hajj-Ahmad[1], Lukas Kaul[2], Carolyn Matl[2], Mark Cutkosky[1]

***Abstract*—We present a solution to the separate challenges faced by suction cups and gecko adhesives for one-sided grasping of heavy, irregular items. The gripping technology combines suction with adhesion for grasping and placing a wide range of objects in packed spaces. Applications include shopping and restocking in retail and warehouse settings where products vary in size and weight and are packed tightly, which limits access. A single suction cup is compact enough to reach and grasp the smallest items (down to 5 cm in size) but cannot provide the shear force needed for handling bulky items. Gecko-inspired adhesion provides extra lifting capability for objects up to 2.3 kg, using a 7.6 x 12.7 cm adhesive swatch – 2.5x heavier than with suction alone. The adhesive is fabricated on a flexible nylon fabric. A small fan blows gently to help the fabric conform to irregular surfaces prior to lifting.**

***Index Terms*—Biomimetics, Grippers and Other End-Effectors, Mechanism Design, Mobile Manipulation, Materials Handling**

## I. INTRODUCTION

WITH the continued development of human assistive robots, the spaces for which we design them are increasingly challenging. Rather than redesigning our environment for robots, we strive to develop solutions that can conform to a human-centered world. In this paper we present a solution for robots that will assist people in retail and stockroom settings, where a wide range of items are tightly spaced on shelves or in cupboards. A prototypical application is a robot shopping assistant, as shown in Fig. 1.

In such settings, the items are often too closely packed for conventional grippers to reach and grasp from the sides. In addition, conventional grippers often perform poorly with irregular and bulky shapes, such as products sold in bags. Soft grippers can perform much better on soft and irregular objects (e.g. [1]–[4]) but these often require even more space around objects to acquire them. Other solutions include specialized grippers with thin fingers and motorized belts for grasping and placing objects [5, 6].

For cluttered spaces and densely spaced items, suction cups have become a preferred solution, widely used in warehouses and manufacturing applications for grasping items from above [9, 10]. For scenarios like the shelving shown in Fig. 1, a single suction cup is appropriate for small items, as long as they present a sufficiently large and flat surface to grip from the front. Large items can be gripped with arrays of suction cups, but then the gripper becomes too bulky to reach and extract individual small items.

Fig. 1. Grasping bulky items from densely packed shelving with the hybrid adhesion and suction picker on TRI's TTT robot [7, 8].

When using suction, imperfect seals on irregular objects can result in failed pick attempts. Moreover, suction cups are primarily designed for providing a force perpendicular to the cup face. The ability to support shear forces is lower, limited by the coefficient of friction and by the compliance of the cups, which makes them susceptible to peeling failures. Some proposed solutions include augmenting suction with grasping using soft materials and high friction (discussed further in Sec. II-A); however, these solutions again require more space around an object.

There are also other solutions that utilize *astrictive* [11] technology such as gecko-inspired dry adhesives [1, 12]–[14], sometimes augmented with electrostatic adhesion [15]. These solutions (discussed further in Sec. II-B) are typically designed, like most suction grippers, for overhead access rather than side access – e.g. with a pair of films tensioned by the

Manuscript received: March, 27, 2023; Revised June, 15, 2023; Accepted July, 11, 2023.

This paper was recommended for publication by Editor Clement Gosselin upon evaluation of the Associate Editor and Reviewers' comments.

[1] A. Hajj-Amhad and M. Cutkosky are with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA. amarha at stanford.edu, cutkosky at stanford.edu

[2] L. Kaul and C. Matl are with Toyota Research Institute, Los Altos, CA 94022, USA. lukas.kaul at tri.global, carolyn.matl at tri.global

Digital Object Identifier (DOI): see top of this page.

IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.

weight of the picked objects. Thus they are well suited for picking items up from a table top or conveyor belt but not for extracting items from a densely packed display.

**Motivation:** Suction devices attempting to pick and place heavy and deformable objects on shelves lack the necessary resistance to tangential loads to prevent heavy objects from sliding on the cup surface, often accompanied by peeling of the cup. In addition, without sufficient compensation for the corresponding moment arm, bulky objects with a center of mass some distance away from the cup will create additional normal contact forces and a bending moment at the cup that causes it to deform and ultimately peel. A solution to this problem is to (i) provide a support to counteract the moment arm and (ii) provide support for the tangential load. A gripper employing directional dry adhesives can provide this support.

**Contribution:** We present a new solution that combines a suction cup with a flexible gecko-inspired adhesive film on a fabric. The combination overcomes some of the previously noted limitations of both suction cups and gecko-inspired adhesives and allows Toyota Research Institute's TTT robot [7, 8] to acquire and place a wide range of objects from densely populated shelves or cupboards in retail, domestic, or stockroom settings.

The technology is suitable for a small mobile robot as it does not require a powerful suction or pneumatic source. It is designed for uni-manual picking operations. The device is retractable, for compactness when the need to pick smaller objects arises. It is fully deployable and self locking with a simple servo and limit switch setup. We make use of a new, resilient, thin film backing material for the gecko adhesives. To promote film conformation to irregular surfaces, we use a gentle stream of air provided by a small fan. Using a single arm on the mobile robot for comparatively heavy and bulky objects frees up the other robot arm with a different gripper (visible in Fig. 1) to manipulate other objects that, for example, have handles.

## II. Related Work

Although the proposed gripper is new, it builds upon prior work on suction and adhesive gripping. In particular, we use a high-flow, low differential pressure vacuum pump with an off-the-shelf rubber suction cup (similar to those used by winning entries in the Amazon picking challenge [16]).

We additionally use directional gecko-inspired adhesives as originally developed for climbing robots and later adapted to grasping and manipulation [1, 2, 17, 18]. The adhesives are manufactured from a micromachined mold, as described in [19, 20].

### A. Augmented Suction Grippers

Suction and vacuum grippers have had considerable success as robotic end-effectors for pick and place operations, and have been adapted into warehouses and assembly lines. With objects that are smooth and rigid, such as glass panels, they can be reliable enough to orient in different poses. When dealing with objects such as boxes, bags, and other irregularly shaped items, often the normal to the suction cup face will be oriented in the same direction as gravity, since a tight seal cannot be guaranteed.

Recognizing suction cup limitations, some researchers have modeled suction cup elasticity and developed multi-chamber cups with integrated sensing [21, 22]. One can also find commercial designs that feature an array of suction cups all oriented face down for package transport in warehouses [10]. If the cups have separate vacuum lines, this solution can also be tolerant of porous, deformable, and bulky objects.

Other work has combined multi-fingered grippers with suction cups [23]–[26]. These designs hold a great deal of promise, especially when the fingers of the gripper can be re-oriented. However, for truly cluttered spaces, like fully stocked grocery store shelves, these designs require more space than may be available. To partially address this issue, Hasegawa et al. [27] use suction to pull an object out from a cluttered shelf and then envelop it with the two gripping fingers. This solution works best for small objects that can ultimately be encompassed by the fingers. Other groups explore the augmentation of friction with suction cups, as in [24], which addressed grasping in wet environments where objects may be slippery. Others have sought to combine pressure controlled compliant surfaces with gecko inspired dry adhesives [13, 28]. In these works, the adhesive is coupled with a suction device and adds adhesion to a compliant surface. These solutions are aimed primarily at top-down grasps and enveloping grasps, which makes them less suited for shelf picking tasks and large items. Attempting to pick heavy deformable objects from one vertical side is susceptible to failure modes including peeling or frictional sliding, which are correlated but occur independently. These occurrences are addressed further in Section III-A.

### B. Gripping with Gecko Adhesives

In previous work gecko-inspired adhesives have been used for wall climbing [17, 29, 30] and for gripping, holding an object between the fingers of a hand [1, 2, 18], or between the end-effectors of a bimanual robot [15, 31]. An important distinction in most of the gripping applications is that there is some internal grasping force, which helps to press the adhesive onto the surface of an object to be grasped. The present application, involving acquiring objects from packed shelves, is conceptually closer to wall-climbing than traditional grasping: we only approach the object from one side and there is no internal force to take advantage of. Consequently, we require some means to make the adhesive conform to irregular surfaces. One possibility is to use electrostatic adhesion, as in [15, 31]. In the present design, a simpler solution is to provide a gentle air cushion using a small fan in combination with fabricating the adhesive on a flexible fabric that drapes more easily than the plastic films used in prior work.

A second challenge is associated with preventing peeling failures. For one-sided or unilateral gripping with directional adhesives, the known solution on flat surfaces is to use arrays of tiles loaded by tendons arranged such that the line of action of each tendon passes through the tile's center of pressure. This is the solution used for vertical surface climbing [17,

IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

30, 32] and for grasping large panels in microgravity [14]. However, grippers composed of flat tiles only work on nearly flat surfaces. As explained in [32] surfaces must be flat to within $10\mu m$ over the length scale of each tile.

For conformation to convex surfaces, the adhesive can be fabricated on a thin film. Then, to promote even shear stresses over the contact patch, tangential forces are applied at one edge of the film [31, 33]. This loading approach works if the film is flexible but relatively inextensible, as large strain in the shear direction will result in stress concentrations and subsequent peeling failure in the adhesive. Finally, to prevent peeling from the upper edge due to moments, we use suction to provide the necessary adhesive normal force.

## III. Design

The solution we propose is designed for a single arm manipulation task.

In an effort to understand what design characteristics lead to a successful object acquisition, we begin with an idealized two-dimensional projection of a suction cup picking an object from the side.

### A. Lifting Forces

Figure 2 depicts a simplified representation of a suction cup attached to the side of an object. The (negative) suction pressure is $p$ and is resisted by contact forces at the cup periphery, abstracted here to upper and lower reaction forces, $f_{c1}$ and $f_{c2}$, with corresponding frictional forces $f_{fc1}$ and $f_{fc2}$. Under loading, the suction cup stretches and rotates by an angle $\theta$.

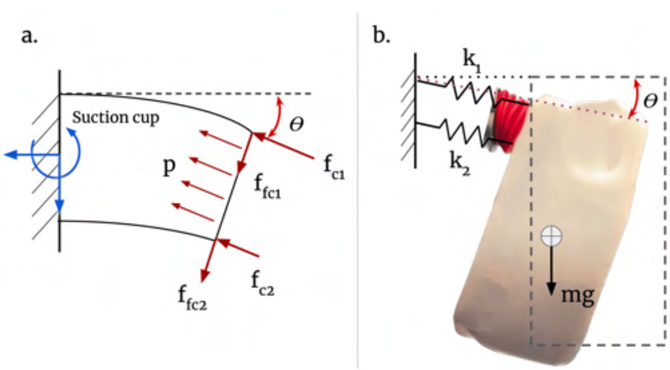



Fig. 2. Idealized two-dimensional representation of suction cup deflected by the weight of an object with side contact.

As the object weight increases, the suction cup can experience failure in two ways:

1) The friction provided by the suction cup face is insufficient to counter the weight of the object, causing the cup to slide off the object.
2) The moment generated by the object's weight is larger than can be countered by the pressure from the suction cup, causing a peeling failure.

These limitations are correlated but independent unless the coefficient of friction is fixed for all objects. In low friction cases, sliding will occur before the suction cup deforms. For objects with high friction, the suction cup will bend and peel before sliding occurs.

Considering the failure modes, we introduce two critical features into the design of the compound gripper. To supplement the friction forces from the suction cup, we introduce a new upward force generated by a contacting patch of gecko-inspired adhesive (Fig. 3). A very small normal pressure, $f_{na}$, holds the adhesive against the object surface as the object is first lifted; subsequently the applied shear load keeps the wedges adhered to the surface, as in other climbing and grasping applications cited in Section II-B.

Additionally, we incorporate a lower support point at **O** in Fig. 3. As an object is lifted, a reaction force, $f_n$, helps to balance the moment produced by $mgl$. Depending on the material used, there may also be a small frictional force, $f_{fn}$, but this is usually negligible in comparison to the other upward forces.

The force balance for lifting is summarized in Fig. 3, taking a two-dimensional projection and assuming that forces in the $z$ direction are negligible. Assuming further that $f_{na}$ and $f_{fn}$ are small compared to other terms and that $r$ is small compared to $h$, the static equilibrium equations become:

$$\sum f_x : -\pi r^2 p + f_n + f_{c1} + f_{c2} = 0 \tag{1}$$

$$\sum f_y : \int f_{sg}\, dA + f_{fc1} + f_{fc2} + -mg = 0 \tag{2}$$

$$\sum M_O : \pi r^2 p(h-r) - mgl - f_{c1}h - f_{c2}(h-2r) = 0 \tag{3}$$

where $A$ is the area of the adhesive contact patch, and the maximum value of $f_{sg}$ is $\approx 60\,\text{kPa}$ under typical loading conditions [19, 34].

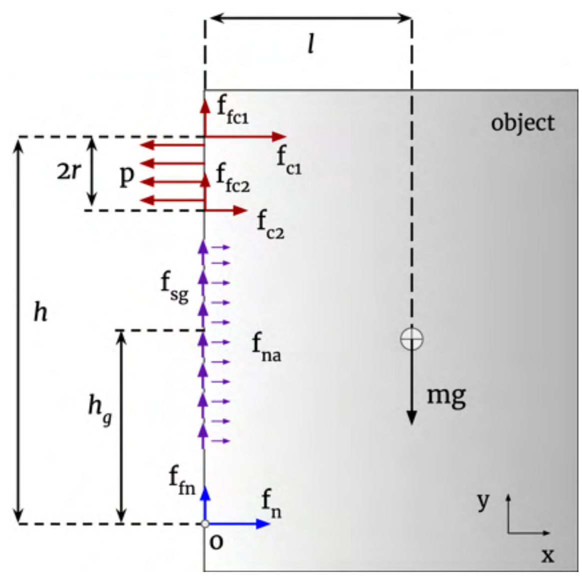



Fig. 3. Two dimensional free body diagram of a generic object picked up by a combination of suction and adhesion in the proposed side pick configuration off a shelf.

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

The force and moment balance equations reveal a couple of design considerations. The first is that increasing $h$ is useful to counteract the effects of the moment, $mgl$. However, if $h$ is too large, the gripper will not be able pick up small objects. The design solution, detailed in Section III-C, is to provide a collapsible arm, so that $h$, and the adhesive patch size, can be large enough to provide significant assistance with heavy objects but retracted for small objects which the suction cup can grasp without assistance. A second observation is that the magnitude of $h_g$ is unimportant, so the adhesive can be located anywhere along the mechanism to maximize its area within space constraints.

### *B. Adhesive subsystem design*

Targeting objects that include irregular shapes and curved surfaces prompts the use of a flexible backing for our adhesive. In previous work, flexible adhesive films were made using thin Kapton (polyimide) sheets [33, 35]. Considering the diverse array of objects and grasp scenarios for our problem space, we desire a more robust material that is not as susceptible to tearing or creasing. Here we employ a Ripstop nylon fabric (FRC13, Seattle Fabrics, Inc.) that is coated with a thin layer of silicone for waterproofing.

When primed with DOWSIL™ PR-1200 RTV Prime Coat Red, the coating provides a strong bond to the silicone elastomer (Sylgard 170, Dow Corning) from which the gecko-inspired adhesive is cast. For maximum performance, the backing film should be flexible but inextensible, to achieve a nearly uniform shear stress when pulled from one end [33]. Therefore we take care to align the nylon Ripstop fibers parallel to the preferred loading direction of the adhesive (i.e., along the $y$ direction in Fig. 3).

To load the fabric in use, we clamp the upper edge between two plates, allowing it to hang freely until it makes contact with a surface. The lower edge is held loosely in place to prevent it from flapping. We use a small DC fan (as found in laptop computers) to create an air cushion that gently pushes the hanging fabric against curved or irregular surfaces to increase the contact area. Once the object starts to lift, the wedges self-adhere under the influence of the applied shear load. Relaxing the shear load causes them to detach (as in the cited previous applications of gecko-inspired adhesives). The air cushion provides a simpler alternative to the electrostatic attraction used in other work [15, 31].

Overall, the suction cup provides the required normal force to the adherend side while the film supports a nearly pure shear force. The stream of air promotes conformation of the film to the object surfaces, but this stream of air can be turned off once lifting begins as the adhesive will remain engaged and taut during lifting as it is continuously loaded in shear.

### *C. Mechanism Design*

As noted above, we desire the adhesive contact area and the total length, $h$, to be large to counteract the moments from bulky objects. For small objects, however, the adhesion apparatus is not needed and gets in the way. Therefore we mount the adhesive, fan, and reaction point, **O**, on a collapsing over-center (self locking) four-bar linkage, as shown in Fig. 4. The mechanism is actuated by a small RC servo motor which is turned off after the mechanism is lowered.

The suction cup is actuated by a high-flow, low-vacuum suction tool with an electric motor so that no encumbering pneumatic lines are required.

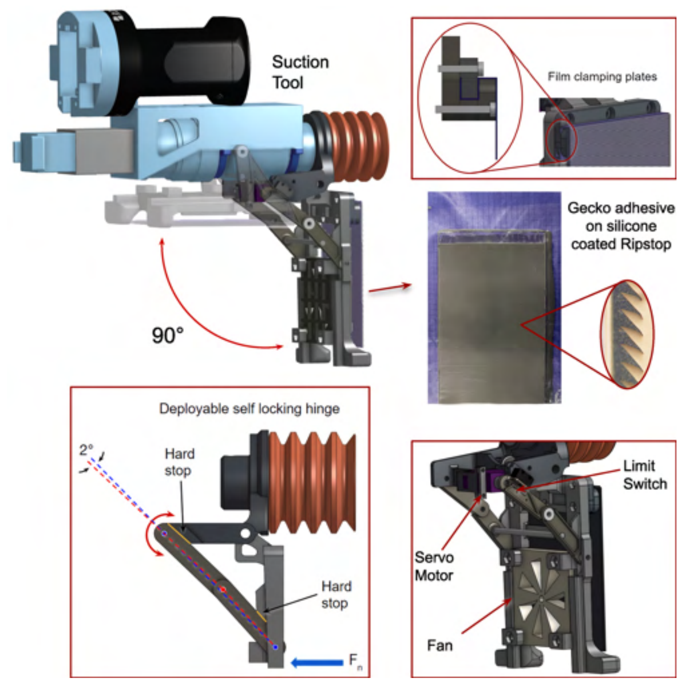



Fig. 4. CAD rendering of the compound tool (top left) with insets of the self-locking linkages (bottom left), the film clamping plates (top right), the gecko adhesive on Ripstop film (center right), and the deployable hinge (bottom right).

For the desired range of objects to be grasped, it was determined empirically that $h = 17.5\,\text{cm}$ provides sufficient support to reliably handle items with a weight of over $10N$. System performance is described in the next section.

## IV. System Performance

We conducted experiments to assess the performance of the gripper on objects with different physical properties.

### *A. Limitation Testing*

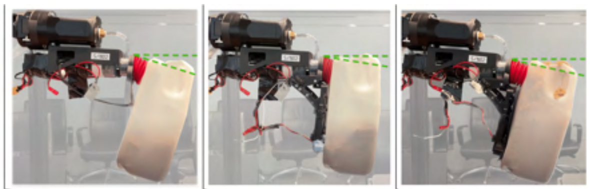
Initial bench-top tests explored the benefits of combining directional adhesion and suction. The grasping tool was mounted to a stand and grasped a plastic 2 L container with a square cross section, into which we gradually added sand until the grasp failed. We then weighed the container. For this container, $l = 4.6\,\text{cm}$ in the notation of Fig. 3.

Each lifting system was tested several times; Table I reports the average maximum loads and standard deviations. For the second and third configurations, the lower contact point (at $h = 17.5\,\text{cm}$ below the suction cup) is covered with rubber, having a coefficient of friction of at least $\mu \approx 0.5$ [36] in contact with common objects. Interestingly, the performance using this contact point and no adhesion (middle column) is slightly worse than for the suction cup alone. The reason is

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

TABLE I
PERFORMANCE TESTING ON MODERATELY STIFF CONTAINER



| **Configuration** | Suction Cup | Suction Cup + Reaction Point + Rubber | Suction Cup + Reaction Point + Gecko Adhesive |
|---|---|---|---|
| **Maximum Weight Lifted** | 9.3 ± 0.2N | 8.2 ± 0.3N | 23.2 ± 0.5N |

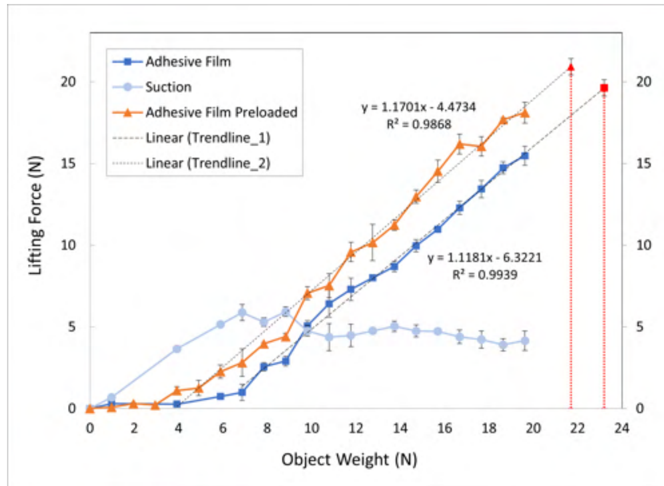



Fig. 5. Force data from FT sensor bench top testing for a rigid object, as seen in Table I. Dark blue squares plot the adhesion lifting force with increasing object weight; light blue circles show the corresponding vertical load supported by the suction up. The second sequence (orange triangles) shows the effect of preloading the adhesive before turning the suction on. The final red triangular and square points indicate the maximum load lifted by the gripper.

visible in the photographs for the first and second column. The sand-filled container is sufficiently heavy that the suction cup has sagged considerably and rotated to an angle of $\theta \approx 15^\circ$ in the first case so that the side load on the suction cup is slightly reduced in comparison to the second case. In comparison, the third case employing both adhesion and the lower support performs 2.5x better. The angle of sagging is approximately as large as in the first case but this is because of the much larger weight.

### *B. Compound Load Sharing Data*

To better understand how much of the object load is being supported by the suction cup versus the gecko adhesive, and to better understand the timing of suction and adhesion engagement, we modified the design of the grasping system to include a force/torque sensor (SRI M3553E) at the film mounting point. We increased the supported weight by increments of 100 g (1 N) and recorded the force measurements from the load cell attached to the adhesive film. Each load increment was tested three times. Figure 5 plots the corresponding adhesive load for the case of an essentially rigid object: a plastic box filled with varying amounts of sand. Figure 6 plots the same data for the case of a highly deformable object: a plastic bag filled with varying amounts of sand.

For the rigid object, we conducted the loading experiment initially with the suction cup active prior to lifting (represented by the blue square data in Fig. 5). A second plot with light blue circles shows the corresponding suction load (total weight minus adhesive load). We then repeated the experiment with the adhesive film being preloaded by $\approx 3\,\text{N}$ in shear prior to activating the suction cup (plotted with orange triangular data points).

For the first loading sequence, we observe that the suction cup load initially increases almost linearly with increasing object weight and then plateaus and slightly decreases as the object weight exceeds 7 N. At this point the suction cup is unable to support more weight without slipping and the remaining weight is borne by the adhesive. For the second sequence, we observe that preloading the adhesive film prior to activating the suction tool shifts the linear trend in the load sharing to begin after 3N of object weight. The adhesive film now supports a larger vertical force for all object weights. If

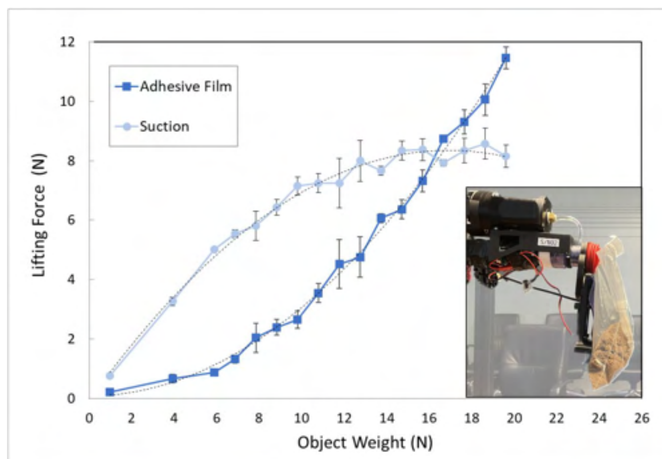



Fig. 6. Force data from FT sensor bench top testing for a highly deformable bag as seen in the inset of this figure. Light blue circular markers represent the vertical force supported by the suction cup and the dark blue square markers are the vertical force supported by the adhesive film.

suction failure is the primary concern, this strategy may be preferred. However, it also resulted in a slightly lower maximum weight due to eventual adhesive peeling: $21.7 \pm 0.5N$, as compared to $23.2 \pm 0.5N$ for the first case with suction engaged prior to lifting.

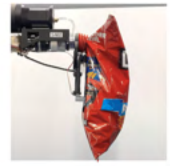
For the case of a highly deformable object, the load sharing transition is less abrupt and timing is less important. The bag forms a strong seal so that the maximum load borne by the suction cup is approximately 8 N, and the adhesive does not carry the majority of the load until the weight exceeds 16 N. We note that most objects will fall along a spectrum between the cases in Fig. 5 and Fig. 6.

Table IV-B extends the tests to a range of common grocery shelf items of varying size, weight and deformability. Suction

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

TABLE II
SUCTION/ADHESION LOAD SHARING ON GROCERY STORE ITEMS NOT RELIABLY PICKED BY SUCTION ALONE

| |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **Description** | Box of trash bags | Vacuum sealed bag of coffee beans | Bag of sanitary pads | 9-pack bag of toilet paper rolls | Bag of chips | Bag of croutons |
| **Material** | Cardboard | Plastic | Plastic | Plastic | Plastic | Plastic |
| **Compliance** | Rigid; Flat | Rigid; Irregular | Slightly Deformable | Very Deformable | Very Deformable | Slightly Deformable |
| **Weight** | 17.2 N | 9.1 N | 5.6 N | 13.7 N | 4.1 N | 5.2 N |
| **Film Shear** | 14.5 ± 0.7 N | 5.1 ± 0.4 N | 2.7 ± 0.1 N | 11.7 ± 2.0 N | 1.83 ± 0.7 N | 2.6 ± 0.2 N |

was engaged prior to the start of lifting for these tests. The table also notes the total weight in each case and the amount of weight supported by the adhesive film. In tests, none of these objects could reliably be lifted using suction alone.

Looking more closely at the data, we observe that for items such as the 9-pack toilet paper bag, due to its uniquely deformable packaging and the difficulty of forming a seal with the suction cup, the adhesive film holds $\approx 88\%$ of the total load. A similar percentile holds for the stiff cardboard box of trash bags. In this case, the seal between the suction cup and the box is sound but the friction is low. Interestingly, adhesion can be high for surfaces that have a low coefficient of friction (e.g. plastic films) as adhesion depends mainly on the surface smoothness [37].

## V. ROBOT EXPERIMENTS

In this section we present the results of tests conducted with the hybrid gripper mounted on a mobile robot described in [7, 8]. Relevant details on the system and strategies are discussed below.

### A. System description

The TTT robot has two 7-DOF arms, a 5-DOF torso, and a 2-DOF neck, all mounted on a mobile base. TTT and its predecessors, developed at the Toyota Research Institute (TRI), have been deployed in grocery picking and other challenge tasks designed to quantify progress and guide future work. The current challenge task requires the robot to shop for 20 random items in a realistic grocery store [8].

The entire task involves the robot navigating to a target object, detecting the object on a shelf using vision, choosing an appropriate grasp planning strategy, acquiring the item while maintaining it in an upright position, and then successfully placing it into a container stationed at the back of the mobile platform (see Fig. 1). The robot is originally equipped with a suction gripper on one arm and a parallel jaw gripper on the other arm. Like most human shoppers, the robot picks objects using only one arm.

To locate an object, TTT relies on a pre-generated map of its environment, created by reconstructing the scene from data collected by a camera-equipped cart that allows for the reconstruction of the 3D space. That information, combined with stock photos of all the grocery store items, allows the robot to perform object recognition using its two stereo cameras. Details of this process are provided in [8].

### B. Grasp Planning

For this new gripper, the grasp approach was based on a visual estimation of the bounding box of the target object. Once the target object is detected, a segmented point cloud of it is extracted using a UNet-based segmentation network. From the segmented point cloud of the item, its dimensions, pose, and surface curvature can all be estimated. Given the target object's class (e.g., bottle or deformable bag) and geometric features, the appropriate tool and grasp strategy can then be selected. For this new tool, the grasp strategy sets the suction cup contact point to be a fixed offset distance (slightly larger than the radius of the suction cup) below the top edge of the bounding box of the target item. This heuristic approach worked well for all our attempted object picks in this paper; however, further optimization of the grasp location can result in more reliable picks and can be tailored to specific items and categories.

### C. Testing

Figure 7 documents different objects that the robot was tasked to locate, identify, and grasp. A successful grasp is defined as one where the tool makes contact with the front face of the object, the grasper securely removes the object from the shelf, and then it transports the object to the robot's carrier box without dropping it prior to the release command.

For objects that require adhesion, the gripper is set to deploy its linkage once the robot has successfully detected the item and the motion planner has positioned the gripper in front of it. At this time, the fan is activated along with suction, and the

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**


Fig. 7. Range of different grocery store objects that the robot successfully picked using the new gripper which it otherwise struggled or failed to grasp with a standard suction gripper. The objects span a range of packaging materials, deformability and weight, reported in Newtons in the top right corner of the robot images.

robot starts to lift. The act of lifting loads the adhesive which assumes a fraction of the total load. To release the object it suffices to turn off the suction and tilt the gripper forward so that the adhesive film immediately peels from the surface. This can also be accomplished by collapsing the linkage without rotating the robot wrist.

As long as the adhesive is not caused to slip on an object, the grasping and manipulation sequence provides a benign loading cycle and the adhesive can survive many cycles. In other work, we have established that gecko-inspired adhesives can sustain at least tens of thousands of loading cycles without noticeable loss of performance – provided that the adhesive is not overloaded [38]. As noted below, an item of future work will be to confirm the expected durability in this application.

The GRASP tool was able to repeatedly secure, manipulate and release all items shown in Fig. 7 without failures. Using a drapable fabric with an unrestrained air cushion consistently produced sufficient area of contact with uniform pressure on the reported variety of items.

## VI. Conclusion and Future Work

We present a novel grasping system that combines the benefits of directional adhesion and suction to grasp both large and small objects from tightly packed shelves. For small items, suction alone is sufficient. The new combination overcomes the challenges that suction cups and gecko adhesives face in picking scenarios with access to only one vertical face.

For large or heavy items, a patch of directional adhesive is brought into contact with the object's front face to provide an additional lifting capability. The adhesive is fabricated on a thin nylon fabric to conform to curved or irregular objects. A small fan provides an air cushion to promote adhesive engagement. The fan and adhesive are mounted on a folding linkage that deploys or retracts, as needed. Together, the adhesive and suction can lift objects considerably bulkier and heavier than suction alone, while still requiring only that the front face of an object be exposed.

Looking ahead, the same hybrid technology can be scaled to handle larger and heavier objects by increasing the power of the suction pump and/or increasing the area of the adhesive, with a correspondingly larger mechanism. This may, however, make the system less attractive for typical small grocery items. Another possible improvement is to coat the adhesive (e.g. as in [38]) to increase adhesion on rougher surfaces.

Durability remains to be demonstrated. As noted above, the adhesive can undergo many attachment/detachment cycles if not overloaded. In a commercial setting, it will nonetheless be necessary to periodically replace the adhesive with a fresh sample. Over time, the adhesive also loses performance as it picks up dust and dirt. In practice, a simple cleaning solution is to have the robot gently press the adhesive against a tacky surface (e.g., a lint roller as used to clean clothing).

Other future areas of contributions also include a comparative study on the effectiveness of different technologies in promoting initial contact including electrostatics or a fluid-filled bladder.

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**

## ACKNOWLEDGEMENT

Amar Hajj-Ahmad is supported by the NSF Graduate Fellowship and completed this research at TRI (Toyota Research Institute) in Los Altos, CA. We thank the mobile manipulation team at TRI for their support. Toyota Research Institute provided funds to support this work.

## REFERENCES


[1] P. Glick, S. A. Suresh, D. Ruffatto, M. Cutkosky, M. T. Tolley, and A. Parness, "A Soft Robotic Gripper With Gecko-Inspired Adhesive," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 903–910, 2018.

[2] W. Ruotolo, D. Brouwer, and M. R. Cutkosky, "From grasping to manipulation with gecko-inspired adhesives on a multifinger gripper," *Science Robotics*, vol. 6, no. 61, p. eabi9773, 2021.

[3] Axel Thallemer and Dominik Diensthuber, "Gripper device for gripping objects EP2735409B1," European Patent Office, Tech. Rep., 2014. [Online]. Available: https://patents.google.com/patent/EP2735409A1/en

[4] Y. Wei, Y. Chen, T. Ren, Q. Chen, C. Yan, Y. Yang, and Y. Li, "A novel, variable stiffness robotic gripper based on integrated soft actuating and particle jamming," *Soft Robotics*, vol. 3, no. 3, pp. 134–143, 2016.

[5] R. Krug, T. Stoyanov, M. Bonilla, V. Tincani, N. Vaskevicius, G. Fantoni, A. Birk, A. Lilienthal, and A. Bicchi, "Velvet Fingers: Grasp Planning and Execution for an Underactuated Gripper with Active Surfaces," in *Proceedings - IEEE International Conference on Robotics and Automation*, 1 2014.

[6] Sean O'Neill, "How Amazon Robotics researchers are solving a "beautiful problem"," 11 2022. [Online]. Available: https://www.amazon.science/latest-news/how-amazon-robotics-researchers-are-solving-a-beautiful-problem

[7] M. Bajracharya, J. Borders, D. Helmick, T. Kollar, M. Laskey, J. Leichty, J. Ma, U. Nagarajan, A. Ochiai, J. Petersen, and others, "A mobile manipulation system for one-shot teaching of complex tasks in homes," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2020, pp. 11 039–11 045.

[8] James Borders, Richard Cheng, Dan Helmick, Lukas Kaul, Dan Kruse, John Leichty, Carolyn Matl, Chavdar Papazov, and Mark Tjersland, "Why we make our robots shop for groceries," 10 2022. [Online]. Available: https://medium.com/toyotaresearch/why-we-make-our-robots-shop-for-groceries-73ea8108caae

[9] J. Tanaka, A. Ogawa, H. Nakamoto, T. Sonoura, and H. Eto, "Suction pad unit using a bellows pneumatic actuator as a support mechanism for an end effector of depalletizing robots," *ROBOMECH Journal*, vol. 7, no. 1, pp. 1–30, 2020.

[10] Schmalz, "Palletizer for Product Layers and Rows." [Online]. Available: https://www.schmalz.com/en/glossary/palletizer/

[11] G. J. Monkman, "An analysis of astrictive prehension," *The International Journal of Robotics Research*, vol. 16, no. 1, pp. 1–10, 1997.

[12] R. Hensel, K. Moh, and E. Arzt, "Engineering micropatterned dry adhesives: from contact theory to handling applications," *Advanced Functional Materials*, vol. 28, no. 28, p. 1800865, 2018.

[13] S. Song, D. M. Drotlef, C. Majidi, and M. Sitti, "Controllable load sharing for soft adhesive interfaces on three-dimensional surfaces," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 114, no. 22, pp. E4344–E4353, 5 2017.

[14] H. Jiang, E. W. Hawkes, C. Fuller, M. A. Estrada, S. A. Suresh, N. Abcouwer, A. K. Han, S. Wang, C. J. Ploch, A. Parness, and M. R. Cutkosky, "A robotic device using gecko-inspired adhesives can grasp and manipulate large objects in microgravity," *Science Robotics*, vol. 2, no. 7, pp. 1–12, 2017.

[15] A. K. Han, A. Hajj-Ahmad, and M. R. Cutkosky, "Hybrid electrostatic and gecko-inspired gripping pads for manipulating bulky, non-smooth items," *Smart Materials and Structures*, vol. 30, no. 2, p. 25010, 2020.

[16] C. Hernandez, M. Bharatheesha, W. Ko, H. Gaiser, J. Tan, K. van Deurzen, M. de Vries, B. Van Mil, J. van Egmond, R. Burger, and others, "Team delft's robot winner of the amazon picking challenge 2016," in *RoboCup 2016: Robot World Cup XX 20*, 2017, pp. 613–624.

[17] E. W. Hawkes, J. Ulmen, N. Esparza, and M. R. Cutkosky, "Scaling walls: Applying dry adhesives to the real world," in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011, pp. 5100–5106.

[18] J. P. Roberge, W. Ruotolo, V. Duchaine, and M. Cutkosky, "Improving Industrial Grippers with Adhesion-Controlled Friction," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 1041–1048, 2018.

[19] P. Day, E. V. Eason, N. Esparza, D. Christensen, and M. Cutkosky, "Microwedge Machining for the Manufacture of Directional Dry Adhesives," *Journal of Micro and Nano-Manufacturing*, vol. 1, no. 1, 2 2013.

[20] A. Hajj-Ahmad, S. A. Suresh, and M. Cutkosky, "Cutting to the Point: Directly Machined Metal Molds for Directional Gecko-Inspired Adhesives," *Journal of Micro and Nano-Manufacturing*, vol. 9, no. 2, 2 2021. [Online]. Available: https://doi.org/10.1115/1.4051406

[21] J. Mahler, M. Matl, X. Liu, A. Li, D. Gealy, and K. Goldberg, "Dex-net 3.0: Computing robust vacuum suction grasp targets in point clouds using a new analytic model and deep learning," in *2018 IEEE International Conference on robotics and automation (ICRA)*. IEEE, 2018, pp. 5620–5627.

[22] T. M. Huh, K. Sanders, M. Danielczuk, M. Li, Y. Chen, K. Goldberg, and H. S. Stuart, "A multi-chamber smart suction cup for adaptive gripping and haptic exploration," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021, pp. 1786–1793.

[23] M. Maggi, G. Mantriota, and G. Reina, "Introducing POLYPUS: A novel adaptive vacuum gripper," *Mechanism and Machine Theory*, vol. 167, 1 2022.

[24] J. A. Sandoval, T. Xu, I. Adibnazari, D. D. Deheyn, and M. T. Tolley, "Combining Suction and Friction to Stabilize a Soft Gripper to Shear and Normal Forces, for Manipulation of Soft Objects in Wet Environments," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 4134–4141, 4 2022.

[25] H. Nakamoto, M. Ohtake, K. Komoda, A. Sugahara, and A. Ogawa, "A Gripper System for Robustly Picking Various Objects Placed Densely by Suction and Pinching," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 6093–6098.

[26] P. Bryan, S. Kumar, and F. Sahin, "Design of a Soft Robotic Gripper for Improved Grasping with Suction Cups," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019, pp. 2405–2410.

[27] 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)*, 2017, pp. 1164–1171.

[28] Y. Hao, S. Biswas, E. W. Hawkes, T. Wang, M. Zhu, L. Wen, and Y. Visell, "A Multimodal, Enveloping Soft Gripper: Shape Conformation, Bioinspired Adhesion, and Expansion-Driven Suction," *IEEE Transactions on Robotics*, vol. 37, no. 2, pp. 350–362, 4 2021.

[29] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, and M. R. Cutkosky, "Smooth vertical surface climbing with directional adhesion," *IEEE Transactions on robotics*, vol. 24, no. 1, pp. 65–74, 2008.

[30] E. W. Hawkes, E. V. Eason, D. L. Christensen, and M. R. Cutkosky, "Human climbing with efficiently scaled gecko-inspired dry adhesives," *Journal of The Royal Society Interface*, vol. 12, no. 102, p. 20140675, 2015.

[31] A. K. Han, A. Hajj-Ahmad, and M. R. Cutkosky, "Bimanual Handling of Deformable Objects with Hybrid Adhesion," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 5497–5503, 4 2022.

[32] E. W. Hawkes, E. V. Eason, A. T. Asbeck, and M. R. Cutkosky, "The Gecko's toe: Scaling directional adhesives for climbing applications," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 2, pp. 518–526, 2013.

[33] E. W. Hawkes, H. Jiang, D. L. Christensen, A. K. Han, and M. R. Cutkosky, "Grasping Without Squeezing: Design and Modeling of Shear-Activated Grippers," *IEEE Transactions on Robotics*, vol. 34, no. 2, pp. 303–316, 2018.

[34] S. A. Suresh, A. Hajj-Ahmad, E. W. Hawkes, and M. R. Cutkosky, "Forcing the issue: testing gecko-inspired adhesives," *Journal of the Royal Society Interface*, vol. 18, no. 174, p. 20200730, 2021.

[35] J. Hashizume, T. M. Huh, S. A. Suresh, and M. R. Cutkosky, "Capacitive sensing for a gripper with gecko-inspired adhesive film," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 677–683, 2019.

[36] M. Mahmoud, "Frictional behavior of different glove materials sliding against glass sheet," *Journal of applied sciences*, vol. 16, no. 10, pp. 491–495, 2016.

[37] M. Zhou, N. Pesika, H. Zeng, Y. Tian, and J. Israelachvili, "Recent advances in gecko adhesion and friction mechanisms and development of gecko-inspired dry adhesive surfaces," *Friction*, vol. 1, pp. 114–129, 2013.

[38] C. Kerst, S. A. Suresh, M. Ferro, and M. Cutkosky, "Pedot: Pss coating improves gecko-inspired adhesive performance," *Journal of Micro and Nano-Manufacturing*, vol. 8, no. 3, 2020.


**IEEE Robotics and Automation Letters (RA-L) paper, presented at ICRA 2024, Yokohama, Japan. Cite as RA-L paper.**