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Design, Fabrication, and Implementation of Self-sealing Suction Cup Arrays for Grasping

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Abstract—**Suction cups have long been used as a means to grasp and manipulate objects. They enable active control of grasp, enhance grasp stability, and handle some objects such as large flat plates more easily than standard graspers. However, the application of suction cups to object manipulation has been confined to a relatively small, well-defined problem set. Their potential for grasping a large range of unknown objects remains relatively unexplored. This seems in part due to the complexity involved with the design and fabrication of various materials comprising the grasper as well as actuators used to enable grasping. This paper introduces the design of a suction cup that is "self-selecting." In other words, the suction cups comprising the grasper do not exert any suction force when the cup(s) are not in contact with the object, but instead exert a suction force only when they are in physical contact with the object. Since grasping is achieved purely by passive means, the cost and weight associated with individual sensors, valves, and/or actuators are essentially eliminated. Furthermore, the design permits the use of a central vacuum pump, thereby maximizing the suction force on an object and enabling some suction on surfaces that may prohibit tight seals. This paper presents the design, analysis, fabrication, and experimental results of such a "self-selecting" suction cup array.**

I. INTRODUCTION

SUCTION technology began to be used for grasping and manipulating objects long before man realized its potential. Octopus, squid, and other cephalopods use tentacles with suction cups to grasp and manipulate food into their mouths. Biological examples of functionality such as these and others have provided the inspiration for numerous robotic techniques [1]-[5], including tentacle arms [4] and suction cups [5], and will likely continue to do so far into the future.

To date, suction has been applied to a wide variety of robotic and automated tasks. One central application of suction technology has been mobility. Numerous wall climbing robots use suction to grasp walls [6], [7], [8], and [9]. Applications for wall climbing include surveillance, cleaning [8], [10], [11], and inspection in tight areas including aircraft [9], [12].

Suction has also been applied to the grasping and manipulation of objects [13], [14], [15]. However, these applications are generally very specific to a particular type of object, with a limited size range and specific geometry. For example, one gripper using suction for object manipulation is for flat, featureless panels [16], while other applications include the movement of limp sheets [17], harvesting fruit [18], [19], and holding documents [20].

It is evident from these examples that suction is useful for grasping a wide range of object sizes and geometries. However, each of the graspers described above is designed for one specific object size and geometry. The ability to utilize this powerful concept of suction on a single grasper for manipulating objects with widely varying shapes and sizes has the potential to expand a robot's object manipulation capability. This capability expansion will be important as robots continue to move into human environments with less predictability and more demands.

This paper presents the design, fabrication, and testing of a concept for a "self-selecting" suction cup array. When the suction cup encounters an object, it opens to allow suction on that object. However, if the cup is not in contact with an object, the cup remains sealed, minimizing leakage through the unengaged cup and maximizing the suction force of the cups that are engaged on the object. Thus, a large number of suction cups could be placed on the manipulator, but it could still pick up small objects. Ultimately, the goal is to expand the usefulness of this suction technology to manipulate objects with a wide range of shapes and sizes using a single manipulator.

II. DESIGN

A. Self-Selecting Suction Cup

To maximize the range of manipulable object shapes and sizes, suction cup size must be optimized. Cup size is important because the smaller the cup, the smaller the item it can pick up. In addition, smaller cups can better accommodate the surface irregularities of the object being grasped if these cups are distributed on a flexible substrate, allowing the robot to adapt to the shape of the object and engage. At the same time, manipulating large objects would then demand a large number of cups. Thus, the design of a single cup must be small and preferably simple.

Weight is also an important consideration. A manipulator's payload capacity diminishes with the weight of

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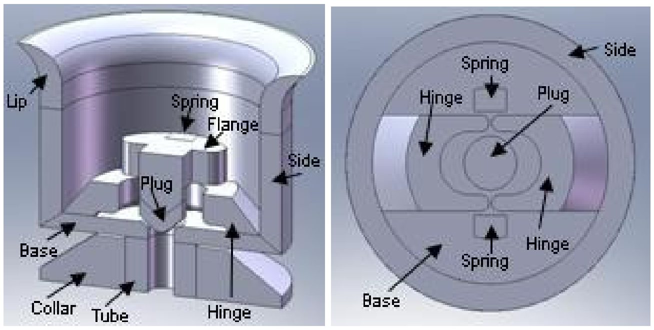

Fig. 1 (a,b). a) Vertical cross-section of the suction cup. This figure shows a 3-D CAD representation of all functional parts. Cup lip, base, tube, springs, and plug are made of rubber. Cup side, collar, hinges, and flange are made of plastic. b) Horizontal cross-section, highlighting the internal structures of the cup with a 2-D CAD representation.

each new component on the manipulator, particularly those on the end, which is the most likely contact location for the object. Therefore, all components of the design needed to operate the cup must be as light as possible.

Based on the aforementioned requirements, the primary principle in our suction cup based grasper design is to utilize the passive reaction forces of the object being manipulated, a concept that is well documented [21], [22], to control air flow. This is achieved by using two materials with differing elastic moduli, making some parts from soft rubber and others from a harder plastic.

Fig. 1(a) shows a vertical cross-section of the design concept as modeled in SolidWorks™. A plug located inside the cup is nominally positioned very close to the suction tube. Due to its proximity to the tube opening, the plug gets sucked into the tube when the central suction line is powered, sealing the hole due to the suction force. The plug's position is maintained through its attachment to a pair of springs connected to the cup's base, shown in Fig. 1(b).

On the other hand, if the cup is in contact with an object, the plug is raised away from the suction tube opening via a hinge action, as shown schematically in Fig. 2. When the suction cup's lip pushes against an object to be grasped, the passive reaction forces from the object push back against the lip of the cup. This force is transferred to the rubber base of the cup, which stretches over the plastic collar, allowing the assembly to compress. The collar acts as a pivot for the plastic hinges located inside the cup, causing them to rotate. Finally, the edges of the hinges slide along the underside of a plastic flange attached to the plug, and the rotation raises the plug away from the suction tube opening. Note that the side of the cup is plastic to maintain the diameter of the cup and prevent the object from crushing the plug. Thus, the cup self-seals (hence no suction force on the lip) when it does not contact the object and self-opens when the lip of the cup contacts the object.

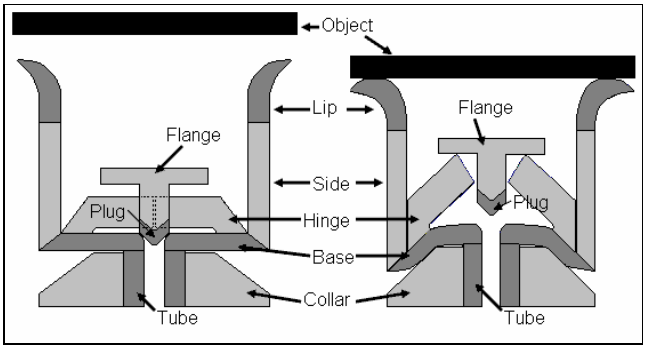

Fig. 2. Schematic of the cup in the uncompressed and compressed positions. Dark gray parts are rubber; light gray parts are plastic.

B. *Size Selection*

Although the device is both simple and effective, a tradeoff is made between the ability to control the plug position and the maximum achievable force imparted to the object. This is primarily due to the springs located inside the cup. To maintain the open position, the springs must be held in tension. If the suction force is the only force holding the object, then the force required to maintain the spring position subtracts from the suction force imparted on the object. However, because the springs are controlled by a hinge mechanism, the suction force is leveraged against the spring force based on the diameter of the cup. Therefore, a larger cup allows longer hinges, giving the suction force a greater mechanical advantage, thereby reducing suction force lost to the springs.

Because one of our primary design goals was to minimize the cup size, the hinges were designed for maximal effectiveness. Based on a minimum manufacturable wall thickness of 1.02 mm, tube diameter of 1.59 mm, and minimum part spacing of 0.13 mm, the internal geometry was designed to the smallest possible size, as seen in Fig. 1(b). A plug displacement equal to one tube diameter was deemed appropriate based upon intuition, and the springs were designed to be strained no more than 0.5 so as to not approach their breaking limit.

To examine the leverage tradeoff, the effective pressure loss was plotted for a range of cup diameters. First, the horizontal distance from the fulcrum (the corner of the collar) to the contact point between the hinge and the flange (the upper corner of the hinge) was computed by:

$$x = h\cos(a + \sin^{-1}(\tfrac{y}{h})) \tag{1}$$

where the parameters are shown in Fig. 3. Assuming a linear stress/strain relationship near the known strain value of 0.5

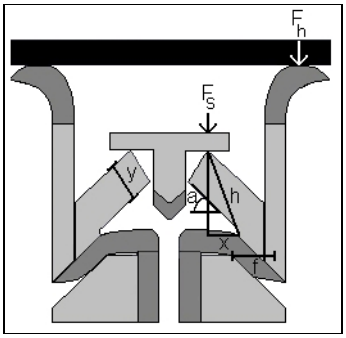

Fig. 3. Schematic of compressed hinge. Relevant variables are defined for Equations 1-4.

(hyperelastic material), the spring force is given by:

$$F_s = 2(\frac{S_a}{S_E})E_s A_s \quad (2)$$

where E_s = known tensile modulus at S_E ,the known strain data point, S_a = actual spring strain, and A_s = area of each spring. The hinge force was then computed using the mechanical advantage of the lever given by:

$$F_h = (\frac{x}{f})F_s \quad (3)$$

where f is the distance from the fulcrum to the outside of the cup at which point the object force acts. Finally, the pressure loss due to the springs, ΔP, was computed by dividing the hinge force by the contact area of the cup, A_c :

$$\Delta P = \frac{F_h}{A_c} \quad (4)$$

Fig. 4 shows the expected pressure loss due to spring force resistance for varying cup diameters. Using this analysis, an outer diameter of 13.97 mm around the cup sides was determined to yield a reasonable tradeoff between size and pressure loss. This was about 10% of the expected pressure based on commercially available suction cup ratings [23].

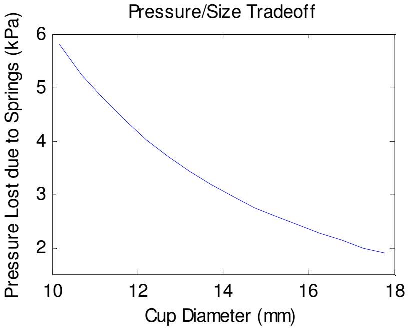

Fig. 4. Theoretical pressure tradeoff. This chart shows the expected pressure loss due to spring force resistance for varying cup diameters.

C. *Finite Element Analysis*

To understand the behavior of the cup under load and optimize design features, a finite element analysis was performed. First, a simple 2-D beam was modeled under a uniaxial load for each material. Material data from Objet's™ website were used to create each beam model [24]. To validate material model parameters, a 50% strain test of each material was performed to ensure predicted stresses matched simulated stresses to within 5%. Once appropriate material models were established, the properties were used to build a geometrically accurate axisymmetric model of the cup without the internal structures. This model was then used to validate a 2-D model of the cup including the hinge.

Fig. 5 and Fig. 6 show the vertical displacement and maximum principal stress results of this 2-D model, respectively. The vertical displacement data was important for determining the appropriate heights for the cup side and the center extrusion of a tool developed to remove support material after manufacturing. While the final angle of the hinge could be predicted analytically based on the collar angle, the plug's vertical offset relative to the contacted object was less easily predicted due to the unknown compression of the cup lip and cup base. Based on the finite element model, a height of 6.35 mm was determined to be appropriate for the cup side, thereby minimizing the overall cup size while preventing the plug from being compressed by contact with even a curved object.

In addition to vertical displacement, maximum principal stresses and strains were analyzed to ensure the design and materials could adequately support potential compressive loading. A stress field analysis revealed stress concentrations at the corner of the cup where the hinge, cup side, and cup base meet. However, the model indicated that despite the stress concentration, the joint would not fail under reasonable loading.

Finally, a 3-D model of the spring was created to

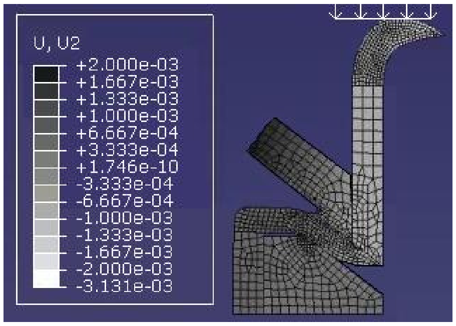

Fig. 5. Finite element analysis showing displacements inside a 2-D cross-section of the cup under external loading.

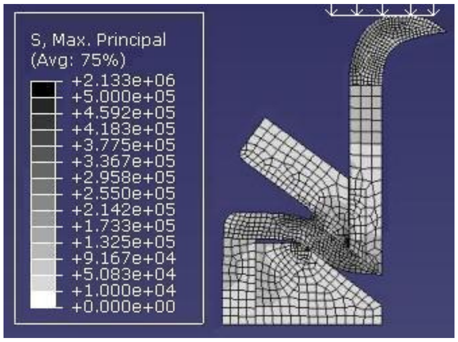

Fig. 6. Finite element analysis showing max principal stress inside a 2-D cross-section of the cup.

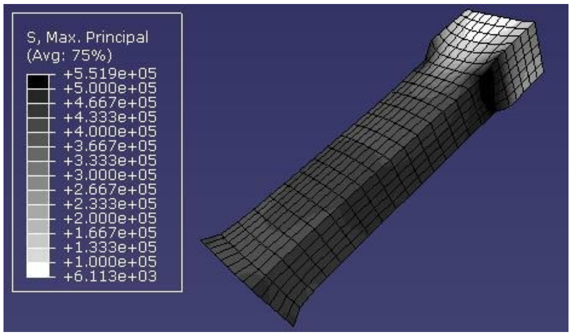

Fig. 7. Finite element analysis showing max principal stress for a 3-D model of the spring.

determine the best method for attaching the spring to the flange. Test geometries showed that attachment at the top surface of the spring was inconsequential compared to the sides of the spring. Therefore, the top of the spring was designed to be flush with the top of the flange, maximizing spring length to reduce strain and thus stress within the spring for the same maximum displacement. Further, an attachment area of 1.2 mm^2 on three sides was determined to be sufficient to handle the stresses on the flange-spring joint due to object loading. Fig. 7 shows the stress field on a 3-D model of the spring given the described boundary conditions.

III. FABRICATION

A. *Self-Selecting Suction Cup*

Due to the small size of each component and the tight tolerances required in their assembly, traditional fabrication methods were considered to be too difficult and time consuming to be reasonable. In addition, the required combination of flexible rubber with solid plastic parts pointed to an obvious technology choice: PolyJet™ by Objet™. This technology enables the production of parts and assemblies from 2 different materials, including plastic and soft rubber – ideal for this design.

For fabrication, the Objet™ materials FullCure®830 VeroWhite and the new TangoPlusBlack® were used for the plastic and rubber parts, respectively. FullCure®830 VeroWhite has a published modulus of elasticity of 2.495 MPa, and while TangoPlusBlack® does not yet have published material data, it should be near that of FullCure®930 TangoPlus, which is hyperelastic with a tensile modulus of 0.263 MPa at 50% strain. This is the approximate maximum strain expected on the springs.

The minimum recommended wall thickness for parts on this machine is approximately 1 mm. Below that, part quality diminishes as was seen with experimentation on various spring sizes that were fabricated. In addition, materials are fused if there is no gap between them. Therefore, a single layer of support material measuring 0.127 mm was required between the plug and the suction tube opening. Because of the chamfered shape of the plug, the suction force was sufficient to seal the opening.

The process of removing the support material from the cup required that each cup be manufactured apart from its underlying structure. For modularity purposes, each cup was epoxied to a test slide manufactured using a Dimension Elite rapid prototyping machine. To prevent leaks, the slides were sealed with a layer of epoxy. A single cup mounted on a test slide is shown in Fig. 8.

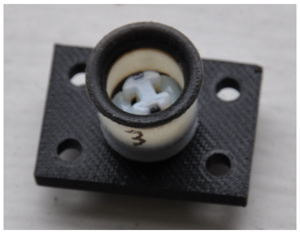

Fig. 8. Single fabricated cup mounted on a test slide.

B. *Flexible Test Rig*

To perform force-displacement and object testing of the cup, a flexible test rig was designed and manufactured. Individual plastic ribs supported each cup, providing a thin rigid surface to resist the passive reaction forces from the object, enabling the cup to compress and thus open. These ribs were connected to one another by flexible rubber tubes. As with the cups, the entire flexible test rig was manufactured by an Objet rapid prototyping machine using FullCure®830 VeroWhite and TangoPlusBlack® materials.

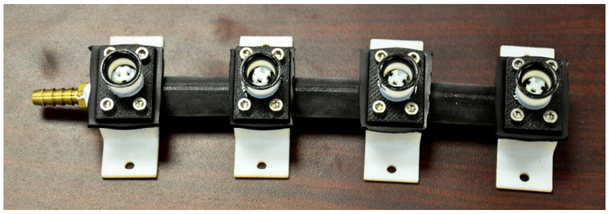

Fig. 9. Fabricated flexible test rig. This was used to perform force-displacement and object grasp testing.

IV. TEST SETUP

To record force and displacement data under both compression and tension, the testing apparatus in Fig. 10 was utilized. The device achieved linear motion by utilizing a lead screw assembly which was powered by a Maxon A-max 32 motor and Maxon GP32 planetary gearhead. Displacement was measured by a US Digital linear encoder with a resolution of 0.05 mm per step. A JR3 6-axis force/torque sensor with a maximum load of 50 N was attached in-line with the stage to measure both tensile and compressive forces. A dSPACE DS1103 controller board (dSPACE, Inc.) controlled the motion and also recorded the force and displacement data. One of the ribs from the flexible test rig described in Section III.B was mounted to the bottom platen, and a compression plate with a glass surface was mounted to the top platen.

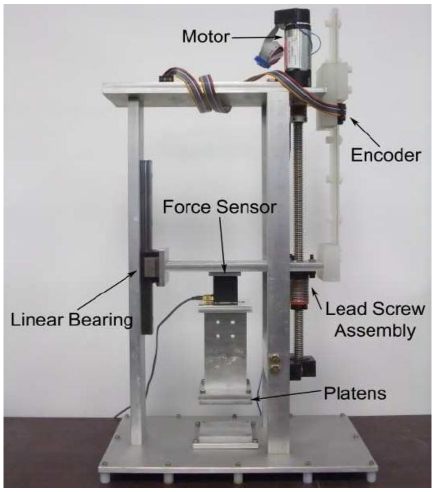

Fig. 10 Experimental setup to obtain force versus displacement data for suction cups with and without plugs.

V. RESULTS

First, a comparison was desired of the effect of the internal cup structures on the forces required to compress the cup. To conserve energy, it is expected that power to the suction pump will remain off until the object has been grasped, and the cups are compressed. Therefore, no suction power was applied during this test. The compression plate was initially placed just above an uncompressed cup. Then, for each cup, it was lowered at a rate of 0.25 mm/s to a maximum depth of 3.5 mm. Fig. 11 shows the results of this test.

Unfortunately, while the absolute displacement of the compression plate was identical for each test, slightly different levels of compression in the underlying slide caused different relative displacements. This makes it difficult to discern exactly how much additional force is required due to the presence of the internal structures. However, if the relative displacements are compared on equal footing based on the initial force increase, the internal cup structures appear to add approximately 2 N of required force to compress the cup. Note that the cups experienced some relaxation after reaching full compression due to the viscoelastic nature of the TangoPlusBlack® material.

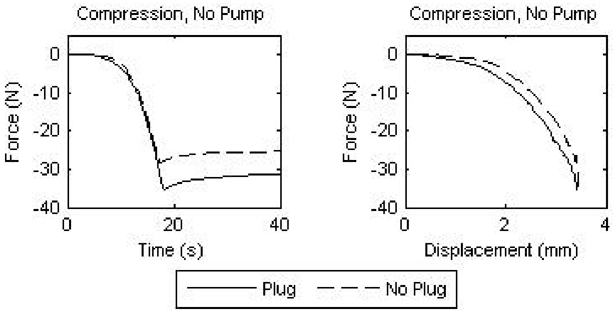

Fig. 11 (a,b). Compression test results without suction. a) Force versus time and b) Force versus displacement on a single cup with (solid) and without (dashed) a plug. Note that positive displacement is compressive.

Normal expected operation dictates that once the initial grasp has been made, the vacuum pump should be turned on to engage the suction. Fig. 12 shows a comparison of the performance between a plugged cup and an unplugged cup. After the initial compression (negative tensile force), the pump was turned on, causing an initial decrease in compressive force (visually a rise to a smaller negative tensile force). Then the compression plate was raised at a rate of 0.25 mm/s to a maximum height of 5.5 mm above the cup's neutral position, sufficiently high to cause the cup to disconnect. The pressure in the line was measured to be 72 mm of Hg, for a load capacity of 691 mm of Hg based on a measured lab pressure of 763 mm of Hg.

As Fig. 12 shows, the actual performance between the plugged cup (solid) and the unplugged cup (dashed) was relatively consistent above the neutral point. Each exerted a maximum force of approximately 9 N. Unfortunately, as the compression plate pulled on the cup above its neutral position due to the suction force, the rubber tube was unable to handle the tensile forces demanded upon it. The tube stretched to the point of failure before the cup released its hold on the object. A stronger tube will need to be designed for future design iterations.

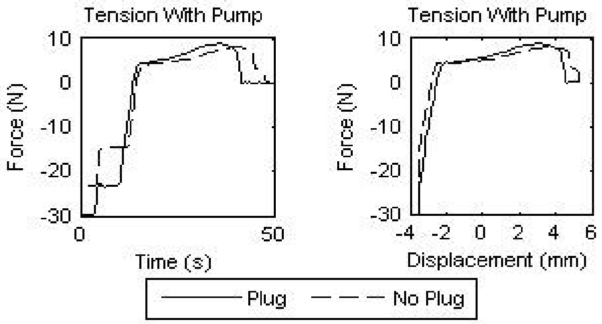

Fig. 12 (a,b). Tension test results. a) Force versus time and b) Force versus displacement on a single cup with (solid) and without (dashed) a plug. Note that positive displacement is tensile in this figure.

To evaluate the effectiveness of our self-selecting cup design, the maximum suction force of the plugged cup was compared to published data on the maximum suction force of a commercially available suction cup mentioned in [23]. For a similarly sized cup (outer lip diameter of 15 mm), a commercially available cup is capable of a maximum force of 580 grams using a load capacity of 609.6 mm of Hg. Multiplying out the safety factor of 2 and normalizing for suction load capacity yields a maximum force of 12.9 N. Thus, in its current form, the self-selecting suction cup is approximately 70% as effective as a commercially available cup. Further, to prevent the cup from failing at the tube and investigate the maximum potential holding force, another test was performed where the compression plate was pulled at a rate of 1.25 mm/s. This reduced the viscoelastic stretching effect and caused the cup to disengage at the lip. For this test, a maximum force of 12.5 N was achieved, demonstrating the potential for the design to perform on par with commercially available cups.

Finally, to determine the effectiveness of the flexible test rig for manipulating actual objects, a coffee cup and a soccer ball were picked up with our prototype (see Fig. 13). This can also be seen in the video submitted with this publication. For each object, one of the suction cups was intentionally left detached to demonstrate that this cup would self-seal, maximizing the suction force on the object from the other three cups. In addition, this test demonstrated that the

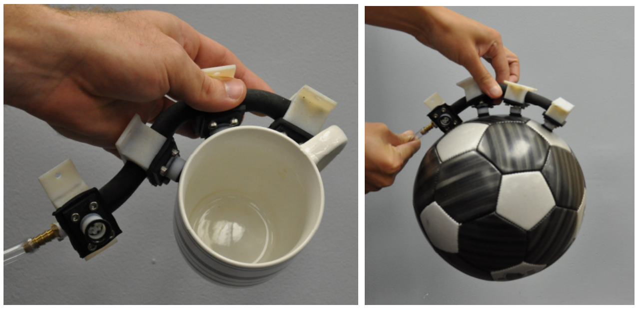

Fig. 13 (a,b). Object test results. On left, a coffee mug was held using 3 of the cups, the fourth being free, demonstrating the effectiveness of the plug. On right, a soccer ball was held in the same manner.

suction force was sufficient to maintain the compressed position of the cup under tensile loading. Thus, the cup did not enter the region to the right of the peak in Fig. 12(b).

VI. CONCLUSIONS

This paper presented the design, fabrication, and testing of a "self-selecting" suction cup based grasper. This cup contains a valve which self-opens using passive reaction forces when the cup lip contacts an object, and self-seals in the absence of contact with an object. While commercial cups seem to outperform the self-selecting cup by approximately 30% for an equivalent outer diameter, this was likely due to the failure of the tube connection to the base of the cup. Thus, the tube was stretched sufficiently that air began leaking in, causing the cup to fail before it released from the object, and yielding a smaller maximum force value than potentially achievable. This will need to be modified in future designs and is likely to substantially improve the comparison to commercially available suction cups.

Despite some under-performance, the self-selecting nature of the design enables force maximization even when not all cups are engaged on an object. The small size, low weight (<1.5 grams), simplicity, and effectiveness should enable the advantages of suction to be applied to grasping a much wider range of object shapes and sizes, as illustrated in this paper. While the array presented in this paper is human assisted, future work will include mounting these arrays on an actuated flexible substrate. Further, others should be able to adapt the design for mounting on existing actuated graspers, enhancing their capability and grasp stability. This may include a limited ability to selectively disable cup arrays to enable the adjustment of a grasp. In summary, irrespective of how these graspers are implemented, we envision that these suction arrays have the ability to greatly expand the utility of robots in uncertain environments, where manipulation of unknown objects is involved.

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