Lee, L. Y., Terrile, S., Roshan, A., Yue, T., Nam, S., & Rossiter, J. M. (2024). Down the Rabbit Hole: Exploiting Airflow Interactions for Morphologically Intelligent Retracting Vacuum Grippers. In *2024 IEEE 7th International Conference on Soft Robotics (RoboSoft)* (pp. 870-875). (IEEE International Conference on Soft Robotics (RoboSoft)). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/RoboSoft60065.2024.10521914

Peer reviewed version

Link to published version (if available):
10.1109/RoboSoft60065.2024.10521914

Down the Rabbit Hole: Exploiting Airflow Interactions for Morphologically Intelligent Retracting Vacuum Grippers

Loong Yi Lee, Silvia Terrile, Ajmal Roshan, Tianqi Yue, Saekwang Nam, and Jonathan Rossiter

***Abstract*— Suction cups and closed bellows actuators are commonly used in industrial pick and place tasks. They can be combined and actuated by a single negative pressure line, providing a simple coupling between suction and actuation. However, the capabilities of this – seemingly very simple – system go beyond just being able to grasp and retract an object. By varying the morphology of the suction cup and by tuning airflow between the two serially connected elements, retraction of the bellows changes and functional embodied behaviours emerge. This work explores the novel concept of flexible Sucking & Retracting Bellows (SuReBellows) comprised of a suction cup and a long-stroke bellows actuator, and how they can be tuned for morphologically intelligent behaviours. Our primary investigation explores how the retraction of the bellows can be tuned to enable "exploration" on the surface of an unknown object in order to make a good vacuum seal contact for grasping. Several suction cup designs were tested in grasping a general object set, by varying the compliance and airflow between the bellows and the suction cup. The results show that SuReBellows can explore the surface of objects and find grasp points just by cycling one pressure signal for actuation, with the search pattern and adaptability encoded in its morphology. The grasping force of the system was then investigated. Finally, demonstrations of interesting applications such as bin picking and grasping in confined environments are shown.**

I. INTRODUCTION

Suction cups are ubiquitous in industry as they are low cost, accessible, and efficient in grasping payloads of many sizes and masses. However, positioning a suction cup for a good grasp can be difficult and can heavily depend on object shape and scene complexity. Sucker placement often falls at the hands of complex vision and manipulator control algorithms [1], [2] which may struggle to generalise for new and unknown objects. There are also complexities in making sufficient soft contact as suction cups need to establish a seal to build up a vacuum, and accurately positioning a suction cup without exerting excessive forces is a topic of interest [3], especially for fragile and valuable objects.

Previous work has sought to increase the adaptability of suction cups by examining hardware design and morphology ([4], [5]). However, these solutions often increase hardware complexity and, as a result, become difficult to control. In addition, they typically require a robot arm for precise positioning and environment exploration. Multiple pumps and controllers are also required ([1], [5], [6]), impacting the cost and feasibility of these solutions. In an attempt to enhance suction, some suction cups self-seal [2], [7], and some suction cups are shaped like bellows [8], [9], establishing a coupling between suction and bellows retraction. That is, once the suction cup seals onto an object, the bellows automatically contract to lift the object. Among the potential of higher adaptability and payload, the interesting "grasp and retract" actuation of these sucker-bellow hybrids is under-explored[10]. Longer stroke bellows may unlock more applications for the suction cup, whether it be grasping in confined spaces such as product bins or pipes, or in more sophisticated tasks which exploit embodied intelligence for increased adaptability.

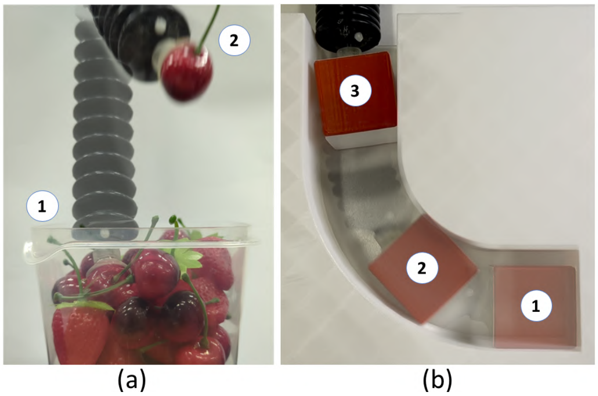


Fig. 1. Image of the SuReBellows bellows-suction cup actuator. (a) Principal behaviour of the actuator autonomously grasping an object from a bin by picking (1) and retracting upwards (2). (b) Superimposed series of images (1..3) depicting the actuator autonomously retrieving an object from a "rabbit-hole"-like confined environment as an example of a novel application. These demonstrations can be found in the supplementary video.

This work pilots an exploration of the interplay between suction cups and bellows actuators as a "smart" grasping actuator. Termed Sucking & Retracting Bellows (SuReBellows), they can simultaneously grasp and pull objects with just one negative pressure line. By tuning the morphology of the suction cup, improvements in grasping performance and the emergence of functional embodied intelligence are explored and demonstrated. Section II introduces the actuator design and describes the behaviours that emerge from simple changes to the suction cup and bellows. Section III demonstrates the functionality of the system via grasping experiments to identify desirable suction cup morphologies

---

This work was supported by EPSRC grants EP/V062158/1, EP/T020792/1, EP/V026518/1, EP/S026096/1, EP/S021795/1, EP/R02961X/1 and EP/L015293/1, and the Royal Academy of Engineering through the Chair in Emerging Technologies scheme (CIET1718/22). TY was funded by Chinese Scholarship Council through award 201906120027. All research data supporting this work is included in this paper.

All authors are with the School of Engineering Mathematics and Technology, University of Bristol and the Bristol Robotics Laboratory, UK. SN is also with the Graduate School of Data Science, Kyungpook National University. Daegu, Korea. Correspondence: `ly.lee, jonathan.rossiter@bristol.ac.uk`

and highlights a variety of applications of the SuReBellows. Section IV discusses the system via force characterisation and observations from the demonstrations. Section V conclude the article with future directions.

II. EXPLORING THE INTERACTION BETWEEN BELLOWS ACTUATORS AND SUCTION CUPS

A. Designing an Actuator with Suction Cups & Bellows

Closed bellows expand under positive pressure and contract under negative pressure. When coupled with a suction cup at the end, the bellows can only contract when the suction cup forms a seal on an object surface. This simple coupling of suction and contraction is fortuitous and applies to both the SuReBellow and other bellows shaped suction cups [11]. Increasing the bellows length has previously been noted as undesirable due to decreased rigidity in the gripper. However, longer bellows unlock interesting capabilities and applications (as shown in Fig.1). Therefore, we explore long stroke bellows actuators and how they might enable different functionalities. The bellows used in this work are BEL-8-250 (Sodemann Industrial Springs) off-the-shelf rubber bellow which has a free length of 375mm. Demonstration of other bellow sizes can be seen in the supplementary video, showing how bellow volume affects retraction speed.

B. Pneumatic Interaction Within the SuReBellows

A core feature of SuReBellow is the use of a single (postive or negative) pressure supply that drives both the suction cup and extension/retraction of the bellows actuators. This allows the use of only one air line and control signal to actuate a "grasp and pull" behaviour. The actuation model of the proposed suction cup and closed bellow system is as follows. In its simplest form, the actuator can be in one of two states when connected to a negative pressure line: State 1 (as shown in Fig. 2(a)) – the suction cup is not adhered to an object, the restrictor is open and air flows through the suction cup into the bellow and out to the negative pressure pump; and State 2 (Fig. 2(b)) – the suction cup is adhering to the object, the restrictor is blocked, no air can flow into the bellow through the suction cup, and negative pressure from the pump contracts the bellow. The actuation of the bellow and the performance of the suction cup are the two fundamental aspects of actuation we will explore. Both suction and contraction are affected by pressure differentials with respect to atmosphere, i.e.,

$$\Delta P_{\text{bellow}} = P_{\text{atm}} - P_{\text{bellow}},$$
$$\Delta P_{\text{suction}} = P_{\text{atm}} - P_{\text{suction}},$$

where P_{atm}, P_{bellow}, and P_{suction} are the absolute pressures of the atmosphere, inside the bellow and within the suction cup. For State 1, the ΔP_{bellow} is mainly caused by the relatively high flow resistance of the restrictor. According to the Darcy-Weisbach equation,

$$\begin{aligned}\Delta P_{\text{restrictor}} &= P_{\text{atm}} - \Delta P_{\text{bellow}} = P_{\text{atm}} - \frac{128\mu Q L}{\pi d^4},\\ \Delta P_{\text{suction}} &= 0,\end{aligned} \tag{1}$$

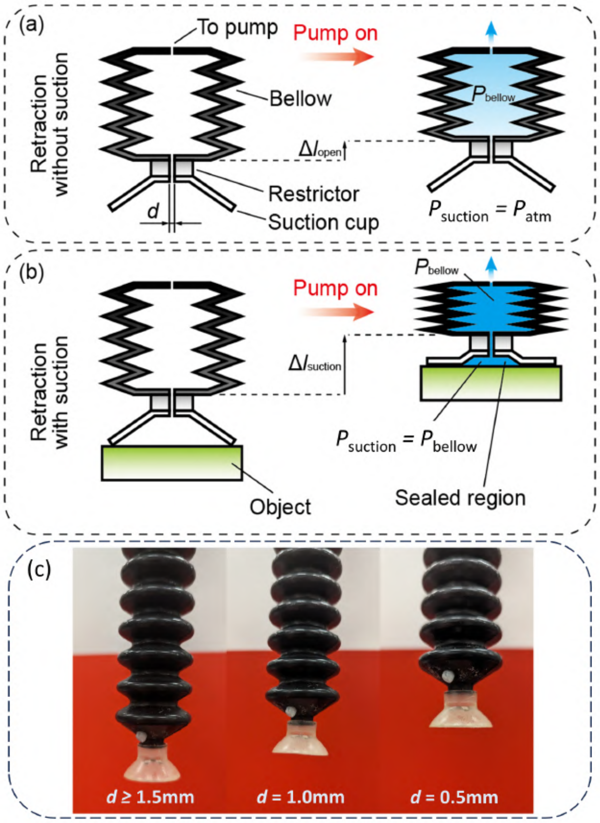


Fig. 2. Diagrams showing the interactions between suction cups and bellows. (a) Diagram of working principle of the system when the suction cup is not in contact with an object. (b) Simultaneous actuation and contraction when the suction cup forms a sealed contact with an object. (c) Images of the free retraction of the system under negative pressure with different restrictor diameters.

where μ is the dynamic viscosity of air, Q is the flow rate, L and d are the length and diameter of the through-hole of the restrictor. Note that, $P_{\text{atm}} = P_{\text{suction}}$ since the suction cup is open, indicating that there is no suction occurring at the suction cup region. Fig. 2(c) shows this free retraction under one second of applied -20 kPa gage pressure with three different restrictor diameters d. It can be seen that the smaller restrictor, d = 1 mm (Fig. 2(c) right), generates the largest retraction, d = 1 mm generates significant retraction, and d = 1.5 mm generates the lowest retraction.

When an object is placed below and in contact with the suction cup, the negative pressure source (connected at the top of the bellow) generates suction between the two. In this case, the seal at the suction interface dominates the flow resistance rather than the restrictor mentioned above. It is important to note that this is not a perfect seal and a small amount of air flows through this seal. The sealed suction region between a suction cup and a flat surface is a ring [12], and now the pressure drop mainly occurs at the suction cup's sealed region:

$$\begin{aligned}\Delta P_{\text{bellow}} &= P_{\text{suction}}\\ \Delta P_{\text{suction}} &= \frac{12\mu Q L_x}{h^3 L_y},\end{aligned} \tag{2}$$

where L_x and L_y are the width and mean circumference of the ring-shaped sealing region. h is the mean gap width between the suction cup disc and the surface. Here we demonstrate why in State 2, the pressure drop is dominated by the suction cup seal and is negligible in the restrictor. According to the equations above, the ratio of seal-induced pressure drop to the restrictor-induced pressure drop is $\Delta P_{\text{suction}}/\Delta P_{\text{restrictor}} = 12\pi d^4 L_x/(128 L h^3 L_y)$, where μ and Q are eliminated since the bellow and the suction cup share the same flow. According to [12], it is common for $L_y/L_x \approx 20$, $h = 10 \sim 100$ nm for a commercial suction cup. Considering the printing quality of our suction cup, we use $h = 1$ μm, i.e., a little rougher than the commercial one. Substituting the design parameter $d = 1.0$ mm and $L = 12$ mm, we obtain that $\Delta P_{\text{suction}} \approx \Delta P_{\text{seal}} \cdot 10^6$, which indicates negligible pressure drop at the restrictor, therefore, both bellow and suction regions share the same pressure.

According to the two equations above, we derive two conclusions which define the two main behaviours of the proposed system. In the case of the vacuuming pump being powered by a constant voltage, State 1 makes the bellow retract a small distance (denoted as ΔL_{open} in Fig. 2(a)). This is because ΔP_{bellow} for State 1 is restricted by the maximum flow rate (~ 40 L/min) of the pump. For restrictor diameter of $d = 1.0$, $\Delta P_{\text{bellow}} \approx -0.47$ kPa is calculated, which contracts the bellows considerably. For larger restrictor diameter $d = 1.5$ mm, $\Delta P_{\text{bellow}} \approx -0.09$ kPa, which retracts the bellow less, as corroborated in Fig. 2(c). In contrast, State 2 not only generates suction on the object, but also makes the bellow retract much more than State 1 (denoted as $\Delta L_{\text{suction}}$).

In addition, we consider the suction force that the system can generate during retraction (State 2). A simplified suction force balance at the suction interface is:

$$\Delta P_{\text{suction}} A = F_{\text{pull}} + F_{\text{deform}}, \tag{3}$$

where A is the sealed area, F_{pull} and F_{deform} are the pulling force and force due to suction cup deformation. Note that the physical models discussed above are simplified without considering large deformations. However, they are sufficient to predict the behaviour of the proposed system.

C. Tuning Actuator Behaviour via Suction Cup Morphology

Suction cups need to adapt to object shapes without needing high pressing force to develop a seal or being so soft that they deform and lose suction. Initial tests with a commercial suction cup made of PVC showed it could not provide the necessary compliance required for this study. As such, ten suction cups were designed and printed using a Statasys Polyjet 3D printer (J826™ Prime), 7 cups using single material and 3 cups using a multimaterial composition. They were printed from Agilus 30 (30A shore hardness) or a combination of Agilus 30 and FLX9860 (30A and 60A multimaterial suction cups). The connection part of the suction cups were printed in FLX9895 (95A) to connect with the bellow via an interference fit. As mentioned earlier, the restrictor diameter, d chosen for the experiments was 1 mm.

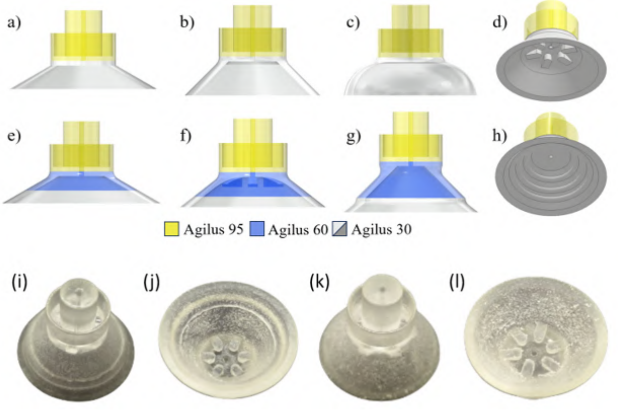


Fig. 3. Images of suction cup morphologies. (a)-(h) CAD images of the suction cups used in experiments. (i)-(l) Images of 3D printed suction cups.

It was found that the orientation of the suction cups during the printing process affects its final behaviour. Initially, suction cups were printed with the suction ring downwards (defined as print angle $\alpha_{print} = 0°$). In this orientation, support material (SUP706B™) was printed inside the suction cup, and consequently the internal surface of the suction cup was textured. Suction cups were then printed with the suction ring upwards and the connector at the bottom ($\alpha_{print} = 180°$). In this orientation, no support material was printed inside the suction cup and its surface was smooth. However, when printing at $\alpha_{print} = 180°$ the outer ring of the suction cup tends to bend upwards, reducing the contact surface with the object and introducing leaks. Therefore, all suction cups used in tests were printed at angle $\alpha_{print} = 0°$. It was obverved that the texture of the inner surface did not significantly affect suction performance.

The suction cups tested here cover a range of different shapes and features including replication of common designs used in industry. The designs tested were the following:

- Standard suction cup with an angle of 30°. This model was designed with two diameters: 34.78 mm, 25.58 mm. (Fig. 3(a)
- Deep suction cup with an angle of 45°. This model was designed with two diameters: 28.14 mm and 24.14 mm. (Fig. 3(b))
- Dome suction cup with an external diameter of 28 mm. (Fig. 3(c))
- Suction cup with internal cleats (radial ridges at the centre). Angled 45°; the external diameter is 28.14 mm. (Fig. 3(d))
- Suction cup with internal concentric rings. Angled 45°; the external diameter is 28.14 mm. (Fig. 3(h))
- Multi-material suction cup with an angle of 30° and a diameter of 34.78 mm. (Fig. 3(e))
- Multi-material suction cup with internal cleats and two angles, 45° in the upper part and 30° in the lower part; the external diameter is 29.76 mm. (Fig. 3(f))
- Multi-material suction cup with two angles. The external diameter is 29.76 mm. (Fig. 3(g))

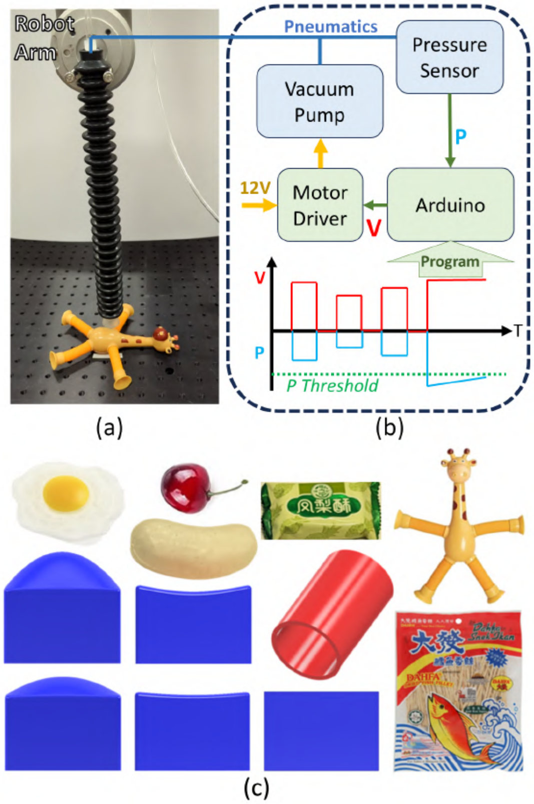


Fig. 4. Elements of “exploration” enabled grasping tests for different suction cup designs. (a) The setup of the SuReBellow on a robot arm to adjust suction cup height above target objects. (b) Control of the SuReBellow during grasping trials, showing an example of voltage and corresponding pressure feedback signals. (c) Objects tested in the experiments.

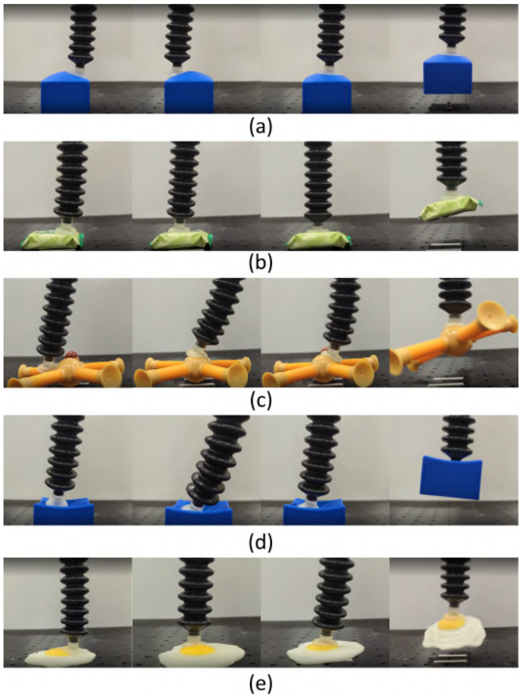


Fig. 5. Image sequences (left to right) of the SuReBellow gripper exploring object surfaces then subsequently grasping them and lifting them up. (a) Lifting the 10mm curvature convex object. (b) Lifting a packet of biscuits. (c) Lifting a toy giraffe. (d) Lifting the 10mm curvature concave object. Detailed views of each grasp can be found in the supplementary video.

III. DEVELOPING EMBODIED FUNCTIONALITY WITH SUREBELLOWS

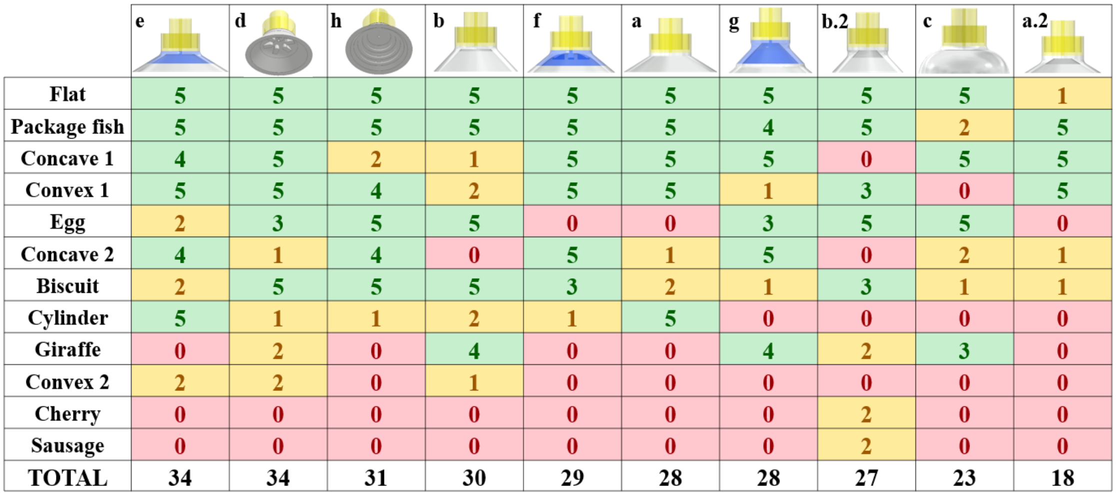
Extending beyond simple grasping, the interaction between the bellows and suction cup can encode functional behaviours in the body of the system. Coupled with smart actuation of the SuReBellows, such embodied intelligence can be directed towards novel applications.

A. *Surface Exploration for Grasping Objects with Unknown Features*

Section II.B showed that in State 1 and given a sufficiently small restrictor, an applied negative pressure will cause the bellows actuator to retract. Turning the pressure off will return the bellow to its neutral length. Furthermore, the imperfections in fabrication of the bellows actuator induce lateral motions at the tip of the suction cup as the bellows contract and relax. These behaviours can be used to actively explore a surface and find a suitable contact seal for the suction cup in order to grasp objects with unknown features.

An experiment was set up (as shown Fig. 4(a)) to observe the grasping capability of the suction cup designs in section II.C via this emergent surface exploration functionality. The top of the SuReBellows are secured as an effector on a UR-10 robot arm, which acts as a jig to position the SuReBellows for different object heights. To enable exploration, a simple pneumatic control system was set up as shown in Fig. 4(b), whereby a vacuum pump (rated 12 VDC, -85 kPa, 40 L/min) is turned ON and OFF at fixed intervals but with different voltage, leading to different flowrates. The motor voltage was randomised between 20-100% of the motors nominal voltage of 12V for each cycle as a way to add noise, preventing the search pattern from converging on a “local-minima” as shown in the supplementary video. A Honeywell 030PG-AA5 pressure sensor was used to measure the corresponding bellow pressure for each cycle. When the suction cup forms a seal on an object and stimulates bellows retraction, a pressure drop is captured by the sensor. An empirically determined pressure drop threshold of -10 kPa enables full retraction of the gripper when an object is within grasp.

The object set used for the experiment includes 3D printed shapes (spherically concave and convex surfaces of 10mm and 20mm height), and objects that cover convex, concave, and deformable object types: a flexible 3D printed hollow cylinder, a plastic sausage, a rubber fried egg, a plastic cherry, a toy giraffe, a small packet of biscuits, and a packet of dried fish strips. All suction cups in Fig. 3 were tested and assigned a score between 0 to 5 for each object, indicating the number of successes out of 5 trials. To allow sufficient time for object surface exploration, each trial was defined as a success if a grasp was achieved within 10 pressure cycles. In these tests, the actuator autonomously searches for a position to generate suction against the surface, simply by turning the pressure signal on and off. This demonstrates the ability of the SuReBellow suction system to adapt itself



	e	d	h	b	f	a	g	b.2	c	a.2
Flat	5	5	5	5	5	5	5	5	5	1
Package fish	5	5	5	5	5	5	4	5	2	5
Concave 1	4	5	2	1	5	5	5	0	5	5
Convex 1	5	5	4	2	5	5	1	3	0	5
Egg	2	3	5	5	0	0	3	5	5	0
Concave 2	4	1	4	0	5	1	5	0	2	1
Biscuit	2	5	5	5	3	2	1	3	1	1
Cylinder	5	1	1	2	1	5	0	0	0	0
Giraffe	0	2	0	4	0	0	4	2	3	0
Convex 2	2	2	0	1	0	0	0	0	0	0
Cherry	0	0	0	0	0	0	0	2	0	0
Sausage	0	0	0	0	0	0	0	2	0	0
TOTAL	34	34	31	30	29	28	28	27	23	18

Fig. 6. Results from grasping tests. Images of each suction shown above their corresponding results. The suction cups in the table are the following: (e) Multi-material 30 degrees, (d) 45 degrees with internal cleats, (h) 45 degrees with concentric ridges, (b) 45 degrees (large diameter), (f) multi-material, two angles, and internal cleats, (a) 30 degrees (large diameter), (g) multi-material with two angles, (b.2) 45 degrees (small diameter), (c) dome and, (a.2) 30 degrees (small diameter). Suction cups and objects have been arranged from best scores on the top left to worst performing combinations towards the bottom right. Each table element shows the grasping success score out of five trials per scenario.

to the environment as a form of embodied intelligence.

All exploration and suction results are shown in Fig. 6, for each suction cup and object. The order of the suction cup depends on the final score (decreasing from left to right), while the object order depends on their total success rate.

Two suction cup designs achieved the same final score: cups 1 and 2. The design with the lowest score was cup 10. The 30° multi-material suction cup design (1) performed well, obtaining a score of 4 or 5 with half of the test objects. Its performance was not appreciable with small or more convex-shaped objects (it was unable to grasp the cherry, the giraffe, and the sausage). The same suction cup design printed in one material (6), however, cannot grasp the more convex-shaped objects or the egg. The suction cup design of 30° with small diameter (10) could grasp only six objects out of twelve, but was very effective at grasping three deformable or curved objects. These results suggest that 30° is a suitable angle for this application and can be improved using multi-material compositions in the suction cup.

The overall performance of the suction cup with internal cleats (2) was the same as the multi-material with 30°, but interestingly, the behaviour differed. For example, both suction cups can grasp the convex-shaped object with maximum height of 10 mm, the concave-shaped object with maximum depth of 10 mm, the flat object, and the fish packet. Both can grasp with some difficulty the convex-shaped object with maximum height of 20 mm and the egg. The differences between these two design is shown with the concave-shaped object with maximum depth of 20 mm and the cylinder, where the multi-material sucker performed significantly better. With the giraffe and the biscuit packet, the internal cleats performed better, especially in the case of the giraffe where the multi-material sucker was not able to grasp. Comparing the performance of the suction cups with internal cleats (2) and those with concentric cleats (3), it was noticed that the latter feature is only effective for the concave-shaped object with maximum depth 20 mm. For the other objects, the results were the same or worse. The suction cup with the dome (9) did not perform well. We note that the suction cup design with 45° and the small diameter (8) was the only one capable of grasping the cherry and the sausage.

In conclusion, the 30° suction cup performed well whenever the surface is large enough and is not highly curved, whilst the 45° suction cup, both with or without internal cleats, is better for small and curved geometry.

B. *Exploration and Manipulation in Complex Environments*

When an object is in a constrained environment such as a parts bin, it can be difficult for fingered grippers to find a suitable grasp. Suction cups have been used in industry for these problems but are often placed on rigid rods to extend reach. SuReBellows are flexible and can retrieve objects from more diverse environments such as from pipes. Demonstrations of bin picking, bin picking with clutter (also seen in Fig. 1(a)), and retrieval of objects from "rabbit hole" like confined mazes (one example in Fig. 1(b)), can be found in the supplementary video.

C. *Investigating the Force Characteristics of SuReBellows*

The dynamic of grasping and pulling raises may have an impact on the payload capabilities of the suction cup. An experiment was set up to test the force of grasping and pulling under a set pressure. Fig. 7 shows the experiment setup consisting of a load cell (App. Meas. UK DBCR compact S beam load cell 100N), and a spring connecting the load cell to a flat planed 3D printed object via kevlar rope and a pulley. While other suction cups need a robot arm to lift the payload, the SuReBellows lift objects up via retracting the bellows. The five best performing suction cup designs from Fig. 6 where each firmly placed on the flat

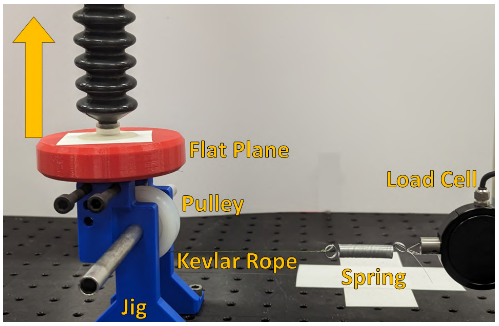


Fig. 7. Image of suction cup grasping force experiments

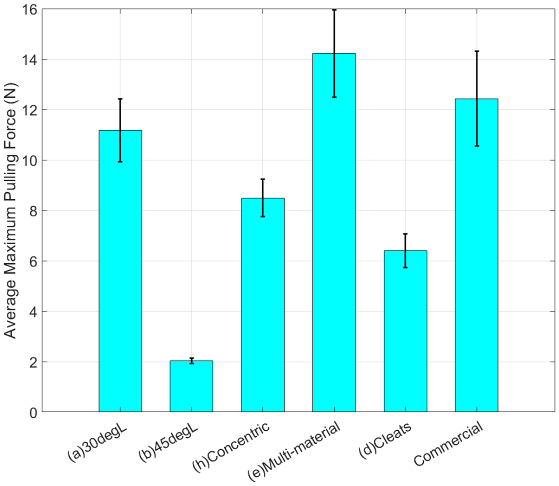


Fig. 8. Results from suction cup grasping force experiments. Numbers in brackets denote associated suction cup design performance in grasping experiments from Fig. 6.

plane object, then the pump was supplied with 12V to retract the bellows, the maximum force exerted before the grasp breaks was recorded. It was observed that the retraction of the bellows provides more force than any of the suction cups can resist. The force at grasp failure will therefore correspond to the suction cup force as described in Eq. 3. Five trials were conducted for each design, including a commercial suction cup (Dobot MG400 suction cup) raised up by the UR-10.

The results in Fig. 8 show that the 3D printed suction cups are as strong as the commercial suction cup, and that the bellows do not compromise the grasping force of these suction cups, which is in line with the interactions described in Section II(b). The best performing 3D printed suction cup is the multi-material suction cup which was also the best at the grasping tasks, suggesting that suction cups with multi-material compositions are optimum. For all suction cups, the pressure in the system during the grasps reached -20 kPa.

IV. CONCLUSIONS

Combining simple suction cups and simple bellows reveals the emergence of higher complexity than one might assume. This work demonstrates that varying the morphology of suction cups is important not just for object conformability, but also in enabling embodied intelligence. The SuReBellow is able to autonomously search the surface of an unknown object to identify suction grasp points. The ability to "jump" around a surface by just cycling the pressure signal demonstrates the emergence of search capabilities from a combination of morphology and environmental interactions. This work shows that there is a place for combinations of simple long stroke bellows and suction cups, and there are various exciting avenues to exploit this simple interaction towards functional behaviours.

Future exploration of the SuReBellows will include tuning behaviour based on the morphology of the suction cup, bellows or the pressure input control. Arrangements of multiple SuReBellows may also develop different functions. Limitations that need to be addressed include tuning the suction cup or bellows such that contact, and hence suction, can be made in confined spaces. Adaptability to more varied surfaces is also required. Multi-material suction cups may play a role in this, as shown in this paper. SuReBellows presents a rich design space for the study of embodied intelligent grasping and manipulation capabilities.

REFERENCES

[1] F. Liu, F. Sun, B. Fang, X. Li, S. Sun, and H. Liu, "Hybrid robotic grasping with a soft multimodal gripper and a deep multistage learning scheme," *IEEE Transactions on Robotics*, 2023.

[2] T. Yue, W. Si, A. J. Partridge, C. Yang, A. T. Conn, H. Bloomfield-Gadêlha, and J. Rossiter, "A contact-triggered adaptive soft suction cup," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 3600–3607, 2022.

[3] A. Koivikko, D.-M. Drotlef, C. B. Dayan, V. Sariola, and M. Sitti, "3D-Printed Pneumatically Controlled Soft Suction Cups for Gripping Fragile, Small, and Rough Objects," *Advanced Intelligent Systems*, vol. 3, no. 9, p. 2100034, 2021.

[4] S. Jeong, P. Tran, and J. P. Desai, "Integration of self-sealing suction cups on the flexotendon glove-ii robotic exoskeleton system," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 867–874, 2020.

[5] 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)*. IEEE, 2018, pp. 6093–6098.

[6] Y. Zhang, D. Yang, P. Yan, P. Zhou, J. Zou, and G. Gu, "Inchworm inspired multimodal soft robots with crawling, climbing, and transitioning locomotion," *IEEE Transactions on Robotics*, vol. 38, no. 3, pp. 1806–1819, 2021.

[7] Z. Wang, S. Terryn, H. Wang, J. Legrand, A. Safaei, J. Brancart, G. V. Assche, and B. Vanderborght, "Self-Closing and Self-Healing Multi-Material Suction Cups for Energy-Efficient Vacuum Grippers," *Advanced Intelligent Systems*, vol. 5, no. 10, p. 2300135, 2023, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/aisy.202300135.

[8] Piab, "Bellow suction cups," https://www.piab.com/suction-cups-and-soft-grippers/round-suction-cups/bellows-suction-cups/ Accessed October 26, 2023.

[9] Y. Yoo, J. Eom, M. Park, and K.-J. Cho, "Compliant Suction Gripper With Seamless Deployment and Retraction for Robust Picking Against Depth and Tilt Errors," *IEEE Robotics and Automation Letters*, vol. 8, no. 3, pp. 1311–1318, Mar. 2023, conference Name: IEEE Robotics and Automation Letters.

[10] S. H. Yoo, M. Kim, H. J. Park, G. I. Lee, S. H. Lee, and M. K. Kwak, "Vacuum-powered soft actuator with oblique air chambers for easy detachment of artificial dry adhesive by coupled contraction and twisting," *Science and Technology of Advanced Materials*, vol. 24, no. 1, p. 2274818, Dec. 2023.

[11] K. Gilday, R. Hashem, A. Abdulali, and F. Iida, "The Xeno-Tongue Gripper: Granular Jamming Suction Cup with Bellow-Driven Self-Morphing," in *2023 IEEE International Conference on Soft Robotics (RoboSoft)*, Apr. 2023, pp. 1–6, iSSN: 2769-4534.

[12] A. Tiwari and B. Persson, "Physics of suction cups," *Soft matter*, vol. 15, no. 46, pp. 9482–9499, 2019.