The Xeno-Tongue Gripper: Granular Jamming Suction Cup with Bellow-driven Self-Morphing

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***Abstract*— Soft grippers have demonstrated significant improvements in grasping in unstructured environments and grasping delicate objects. However, there are limitations preventing more widespread real-world use, from low holding force, high control complexity in diverse object sets, and challenges picking in clutter and more. We present a soft adaptive suction cup design—featuring a morphing granular jamming cup augmented by a suction-based 'Xeno-Tongue'—which can pick and handle diverse objects under a variety of environmental constraints, or lack of. The gripper combines soft suction with an in-built pulling mechanism, i.e., the tongue provides active pulling for automatic suction cup shape adaptation to objects independent of the surrounding environment. We characterise and predict the grasping performance on a series of benchmarking surfaces. Additionally, grasping real-world objects, in clutter and a simulated harvesting environment, using an unmodified control strategy demonstrates adaptability and agility for rapid application in agriculture and other industries.**

I. INTRODUCTION

Soft robotic grippers are being increasingly used for their ability to passively adapt to significant environmental uncertainties [1], [2]. With industry and research continually moving towards more agile tasks with greater variance [3], [4], [5], pick and place robots should be able to grasp diverse objects with minimal information and control complexity [6], [7]. Agriculture is an important example, where robotic harvesting and automation of warehouse tasks such as quality control and packaging are in demand [8], [9]. These tasks require a robotic gripper that can adapt to a wide variety of shapes, sizes and weights, while minimising damage and allowing picks in different environments, such as suspended when harvesting and from cluttered bins and conveyors [8], [10].

Soft grippers are inherently suited to adaptive pick and place without damage [2]. However, many soft grippers rely on enclosing objects, such as soft pneumatic finger grippers [11], [12] or the universal gripper [13], which is often not possible in clutter or dense harvesting [8]. Suction cups can work around this limitation by only needing a small contact area to grip and with simple control [14], [15]. Though, suction cup grippers are highly sensitive to surface texture and shape, hence they have seen limited use outside of highly controlled factory settings [16], [17].

Some gripper designs attempt to cover the limitations of suction cups and soft enclosing grippers by integrating multiple gripping modes [11], [18], [19], [20]. By extending gripper modality, control becomes increasingly complex

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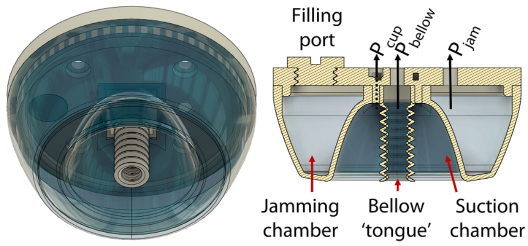


Fig. 1: Jamming cup and soft 'tongue' overview. The jamming chamber enables suction cup shape adaptation. Bellow 'tongue' allows picking of smaller objects and an initial pulling force for jamming chamber deformation when objects are unconstrained.

which is undesirable for agile systems [6], [21]. Other designs attempt to overcome limitations with soft, adaptive suction cups [21], [22]. One such design is the jamming suction cup [15], [20], which can essentially morph the shape of the suction cup to the object being picked. Though, adaptive suction cups often rely on a reaction force to push against and morph the cup shape, limiting the environments it can pick from [22].

In this paper, we present an evolution of the jamming cup design [15], which features a 'Xeno-Tongue' bellow used to provide an initial force for cup shape adaptation, greatly reducing constraints from picking environments. We demonstrate the gripper capabilities on a variety of benchmarking surfaces, including narrow cylinders and angular surfaces, traditionally challenging for suction cups [16]. Additionally, we demonstrate the capabilities with real-world objects, showing successful grasping on object size ranges 17 mm and up, object weight ranges 0.004–0.942 kg, and simulated harvesting.

The remainder of the paper is structured as follows: Section II outlines the gripper design and models its operating principles; Section III outlines the experimental setup used to validate the gripper behaviours and test the performance on real-world objects; Section IV contains the experimental results, first characterising the bellows and gripping forces, then evaluating the gripper potential on benchmarking surfaces, finally on real-world objects in different environments. Section V details the conclusions of this paper.

II. MODELS & METHODS

A. Gripper design

a) Jamming cup: The gripper primarily functions as a shape adaptive suction cup. The cup which forms the suction

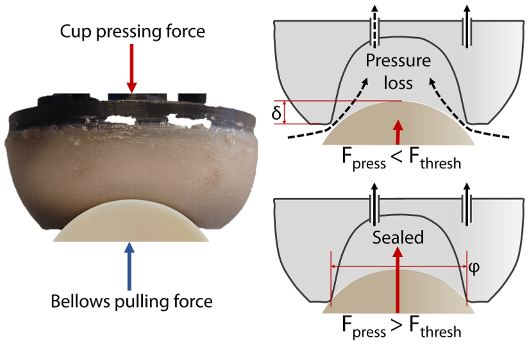


Fig. 2: Jamming cup pushing model. For success suction chamber seal (and successful grasping), a force is needed to deform the jamming chamber (deflection δ), either from pressing into a constrained object, or a small pulling force from the bellows. The amount of force required depends on the object geometry, the cup size (diameter ϕ) and cup stiffness.

chamber is constructed of silicone for high compliance and shape adaptive capabilities, Fig. 1. The holding force that can be generated is proportional to the area the pressure is acting over, therefore, the suction chamber requires structural integrity to maintain this area. Granular jamming allows online control of stiffness [13]. Surrounding the suction chamber with an isolated chamber filled with granular material allows compliance for shape adaptation, then structural rigidity when grasping. Previous work showed successful shape adaptation up to 7 times surface shape variation and an order of magnitude improvement in leak resistance to textured surfaces, such as oranges, than off-the-shelf suction cups [15].

b) Bellows: Fig. 1 shows the bellow 'tongue' and its cross section. This is placed centrally in the adaptive cup and is used to form an initial grasp on an object. The bellows contract under vacuum, generating a pulling force towards the gripper base. The small size allows reliable air seals on varied objects, though with only a low force. The low force is sufficient to pull the object into the adaptive cup for the initial deformation required to form a seal with the suction chamber. Additionally, the small bellow cup can allow grasping of objects smaller (down to 10 mm) than the aperture of the large cup (40 mm).

c) Enclosure model: Fig. 2 shows the operation of the jamming cup shape adaptation. For a seal in the suction chamber (Fig. 1), a surface must be in contact around the entire cup perimeter. Whilst the jamming chamber is soft, force is required to deform it to the contours of the surface. This force can originate from a reaction force, if the object is constrained on a surface, or from a small pulling force from the contraction of the bellows. When picking, the bellows, jamming and suction are activated in that sequence. When picking a constrained object, either reaction force from the constraint or the bellows pulling can provide the initial deformation; for controller simplicity, the same procedure as unconstrained picking can be followed. Equalising chamber pressures with atmospheric pressure releases any holding force when placing objects.

TABLE I: Silicone bellows deflection parameters

Symbol	Parameter	Quantity
k	Spring rate	0.06533 N/mm^2
B_c	Bellows number of convolutions	8
B_{cl}	1/4 of convolutions length	
M_r	Mean radius	2.5 mm
E	Young's modulus	3.7476e+03
t	Wall thickness	0.885 mm
E_a	Effective area	44.178

d) Fabrication: The gripper itself is constructed from three components: the soft membrane which forms the jamming and suction chambers, this is cast in a single step from silicon 00-10; a 3D printed base containing air ports and mounting points; and the bellow, prefabricated with injection moulding in silicone A50. An alternative bellow design is considered with thin walls and softer material to minimise stiffness and increase holding force, this is printed with a Stratasys Connex3 primarily in Agilus30 (shore A30) and secondarily Rigur for reinforcement under vacuum, Fig. 3a and b. The components are press-fit together and sealed using the adhesive Silpoxy.

B. Bellow Modelling

Bellows are cylindrical shapes with convolution, allowing retraction and expansion, used in soft robotics for actuation [23]. Several bellows' parameters influence the force-displacement characteristics, including material Young modulus, wall thickness, average diameter, fabrication technique, and the number of convolutions. Silicone bellows operate as a spring with two forces: pressure thrust when pressure is applied and retrieving force when pressure is released. The maximum pulling force is given by the vacuum pressure and area it acts on the object, the retrieving force reduces this proportional to the bellows deflection.

The pressure thrust can be calculated from the applied force, expressed as $B_p = F/E_a$. The longitudinal displacement of the bellows can be identified from the bellows' parameters and represented as [24], [23]:

$$D = \frac{2B_cB_{cl}F}{\pi M_r t E}. \tag{1}$$

Table I illustrates bellow parameters. The relationship in (1) is linear and can be altered when pressure thrust affects the elastic limit E of the bellows. The number of bellows convolutions B_{cl} defines the displacement length of a bellows, in which a larger B_{cl} provides more elongation. Increasing wall thickness t increases spring stiffness (K). K can be found from the retrieving force of Hooke's law ($F = -K/D$).

Several design choices can be made to optimise the bellows pulling force over the desired deflections. A softer material reduces retrieving force and reduces air leakage on

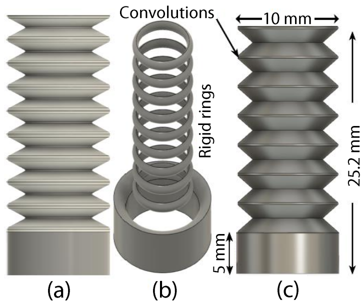


Fig. 3: Two bellows models were used in this work. (a) Soft material (shore A30) bellows with reinforcing rigid rings (b) to keep the whorl open. (c) Homogeneous silicone (shore A50) bellows, cross section in Fig. 1.

textured surfaces, greatly increasing pulling force. However, this can introduce structural integrity issues which require features such as reinforcing rings (Fig. 3b) to prevent internal buckling. These rings can in turn alter the bellows force/displacement characteristics.

C. Picking model

Combining the enclosure and bellow model, we can predict surfaces that can successfully be picked. Bellows force, F_b, can be validated against (1) for pulling force at bellow displacements δ. Pressing force required to generate a seal, F_p, is measured. Then for each surface, if the bellows pulling force is greater than the required pressing force, $F_b > F_p$, successful picking when unconstrained is predicted. This is the maximum net pulling force:

$$F_{max} = F_b - F_p \tag{2}$$

The bellows and soft cup displacements depend both on the surface geometry as well as the alignment of the surface with the cup (in Fig. 2, if the curved surface is offset relative to the cup, higher deformation is required on one side to generate a seal). Counteracting this is self-centering, as the bellows pulls towards the center of the cup. In a hanging case, to pull towards the center, the object weight, F_m, should be overcome. An estimate of the minimum net force is given by:

$$F_{min} = F_{b_{off}} - min(F_{p_{off}}, F_w) \tag{3}$$

Where $F_{b_{off}}$ and $F_{p_{off}}$ are forces from surfaces offset by a constant distance expected by inaccuracy in object localisation.

III. EXPERIMENTAL SETUP

To evaluate the design of the proposed gripper and its behaviours, three experiments are performed along with a demonstration on real-world objects. All three components of the gripper, i.e., vacuum cup, jamming chamber, and bellows, are connected to the same vacuum source (vacuum ejector SMC ZH10B) through independent 3-port solenoid valves (Fig. 4a). To ensure cup pressure is weaker than that in the jamming chamber, preventing suction chamber collapse [15], the pressure in the vacuum cup is regulated to -80 kPa.

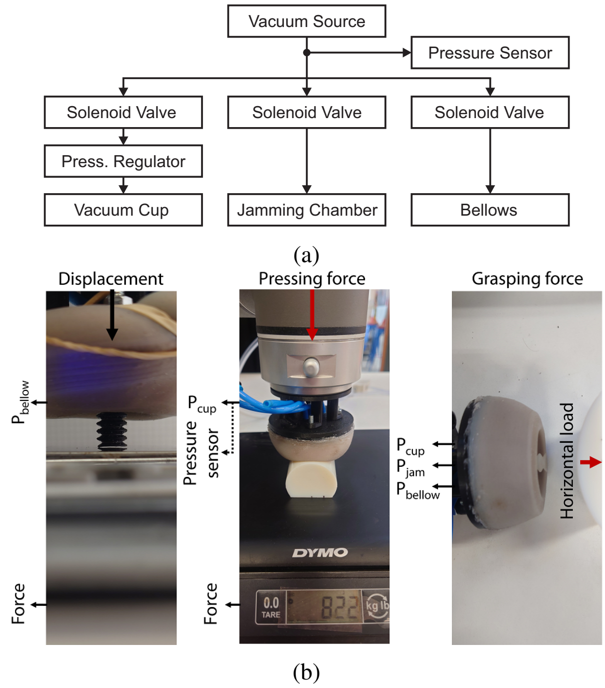


Fig. 4: Experimental pneumatic circuit and setup. (a) Pneumatic circuit with a single -90 kPa vacuum source and independent control of output pressures with 3-port solenoids. The suction chamber is regulated to -80 kPa. (b) Bellows force/displacement characterisation (left); pressing force characterisation (center); freestanding grasping verification (right).

To measure the force-displacement characteristics, the displacement is controlled in the vertical direction using a UR5 robotic arm. The pulling forces due to bellows suction at different displacements are recorded using digital scales (Fig. 4b left). The vacuum and jamming chambers are disabled in this experiment.

The second experiment measures the pressing forces required to form air seals against various surfaces (sample surfaces seen in Fig. 6a). The UR5 presses down until a seal is formed—detected by monitoring for a pressure spike an SMC PSE543A-R06 sensor—or the robotic arm force limit is exceeded. Once the seal is detected, the pressure in the cup is disabled and the force values from the digital scales are recorded.

The third experiment validates picking performance when combining the bellows and the suction cup. Sample surfaces are placed freestanding (Fig. 4b right) and the gripper is driven to grasp from the side with the following procedure:

- Activate bellows suction
- Move to object (bellows should seal and pull object)
- Activate jamming and cup suction to securely grasp

With a digital force meter, the grasped surfaces are loaded, pulling away from the gripper, until failure.

The final demonstration involves grasping real-world ob-

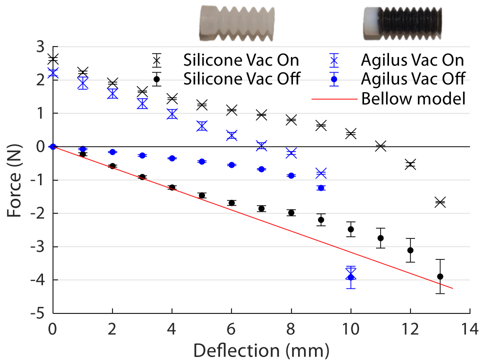
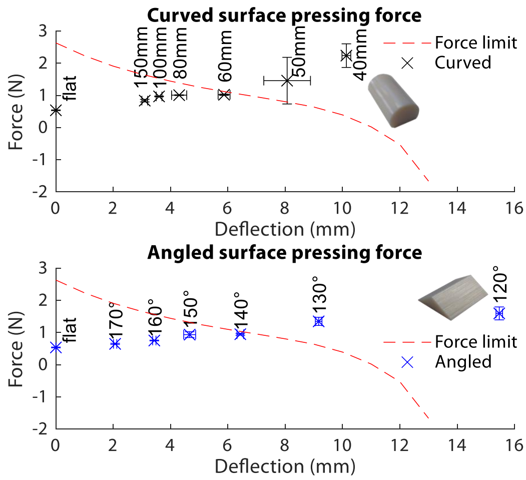
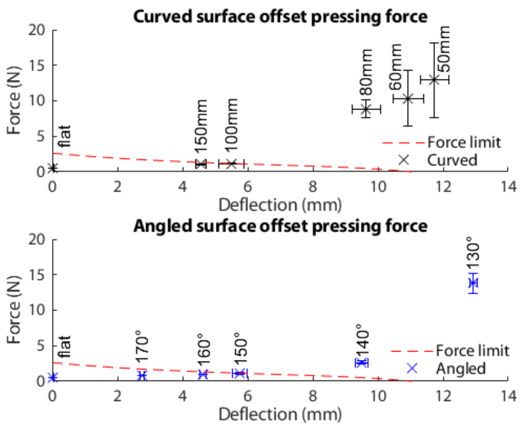


Fig. 5: Bellows pulling force curves. Silicone bellow (black), with -80 kPa vacuum on (cross) and off (circle), matches with linear model (red — from (1)) for low displacements. Agilus bellow, lower stiffness and maximum displacement, internal pressure loss causes faster drop in pulling force.



(a)



(b)

Fig. 6: Cup pressing force before a vacuum seal is detected against deflection (Fig. 1), compared with measured bellow pulling force for each deflection (red line — Fig. 5). Curved surfaces (black) from infinite (flat) to 40 mm diameter. Angular surfaces (blue) from 180° (flat) to 120°. (a) Gripper and surface are aligned. (b) gripper and surface are offset by 10 mm. Picking success (with no constraint in the pressing direction) is predicted by the envelope underneath the red line.

jects. A variety of fruits are chosen as these highlight adaptivity required for diversity in shapes, the need for soft handling to reduce damage, and the different environmental conditions they can be found in (clutter and hanging). In different environments the same grasp procedure as above is performed and the grasping success rate is recorded.

IV. EXPERIMENTAL RESULTS

a) Bellows force: Fig. 5 shows the force/displacement curve for two bellow designs, silicone and Agilus (Fig. 3). The curves with vacuum off show the Agilus design is softer, though has a shorter maximum displacement. With vacuum on, the silicone cup has greater pulling force over its larger displacement range, likely due to pressure loss from slight permeability in the Agilus bellow, hence the silicone bellow is used for all further experiments.

A linear model of the bellows displacement was generated. Inputting the internal diameter of the silicone bellow gives the red line in Fig. 5. The linear spring model matches reality for small displacements, though non-linear behaviours are observed where stiffness decreases as bellow convolution is flattened, then increased again once maximum displacement is reached.

b) Enclosure force: Fig. 6 shows the pressing forces for sealing deformation with different shapes, against the deformation of the bellows from geometry (Fig. 2), compared with the predicted bellow pulling force. If the bellows pulling force exceeds the sealing force, successful picking is predicted. The red line shows the maximum bellows pulling force. Therefore, any point above the red line we predict the bellows will not generate sufficient pulling force, i.e., picking without constraints is predicted to fail. From Fig. 6a: we expect curved surfaces with diameters over 60 mm, and angled surfaces greater than 130°, to succeed.

When pressing at an offset, Fig. 6b, a larger deformation is required, hence large force and displacement for each shape. The results predict only diameters over 100 mm and angles over 150° to succeed. Though, this does not account for any self-centering effects of pulling on an object with the bellows.

c) Freestanding grasping: Fig. 7 shows the holding force measured when grasping surfaces placed freestanding, i.e., unconstrained in the direction of picking. The frictional force on each was negligible (<0.01 N). When the gripper is centered on the surfaces and used to pick, the curved surfaces with diameters 80 mm and above are successful, this is within the error of Fig. 6a, where 60 mm is on the borderline. For angled surfaces, as predicted, angles 140° and above are successful. When picking at an offset, Fig. 7 red, more surfaces are successful than predicted. Likely due to self-centering effects when pulling the freestanding surfaces with the bellows.

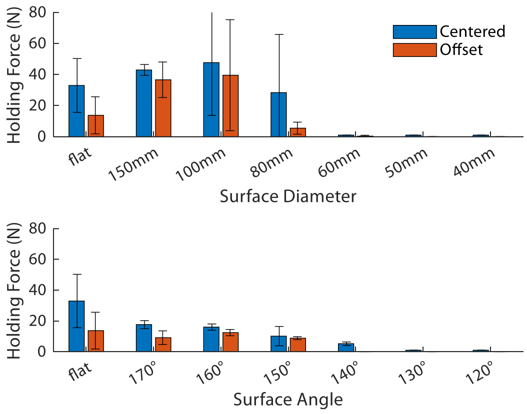


Fig. 7: Freestanding grasp holding force for curved (top) and angular (bottom) surfaces. Measured force when grasping aligned surface (blue). Measured force when grasping surfaces offset by 10 mm (red). Holding forces under 2 N are from the bellows alone.

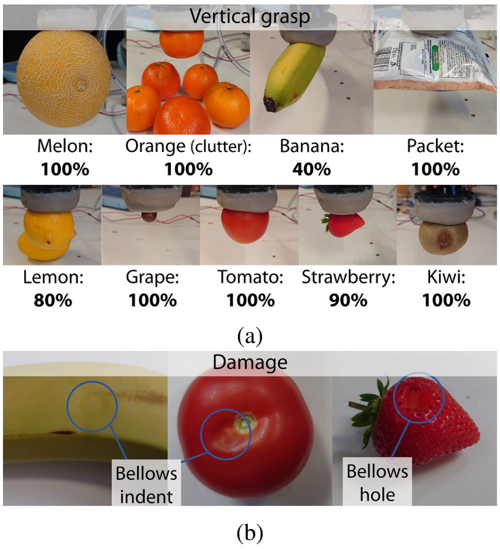


Fig. 8: Vertical grasping results on varied and delicate objects. (a) grasping success rate on the objects from Table II. (b) Cases of damage from excess pressing and suction.

The horizontal holding force changes depending on the quality of the seal between the cup and the surface. A slightly curved surface forms a high-quality seal, needing little force to cause the required deformation, whereas flat surfaces may not always seal if the pressure around the edges of the cup are uneven. Angled surfaces generally have lower holding force, the discontinuity can generate high stresses in the cup material resulting in a weak point in the seal.

Removing the bellows and repeating this experiment, every surface except for the flat surface, are unsuccessful. This is expected as the next 'easiest' surface to grasp in this way needs a minimum force much greater than the sliding friction.

d) Adaptive grasping: Fig. 8a shows the gripper picking a variety of fruit (Table II) along with the success rate

TABLE II: Fruit parameters, rough shape and upper and lower bounds of net pulling force.

Fruit	Mass (g)	Size (mm)	Shape	F_{max} (N)	F_{min} (N)
Melon	942	130	Sphere	1.10	0.54
Orange	64	52	Sphere	0.37	-0.15
Banana	204	17	Curved	-1.50	-3.54
Packet	24	120	Flat	1.05	0.81
Lemon	124	73	Curved	0.18	-0.07
Grape	4	17	Sphere	n/a	n/a
Tomato	110	61	Sphere	0.51	-0.10
Strawberry	26	35	Conical	n/a	n/a
Kiwi	75	74	Curved	0.20	-0.07

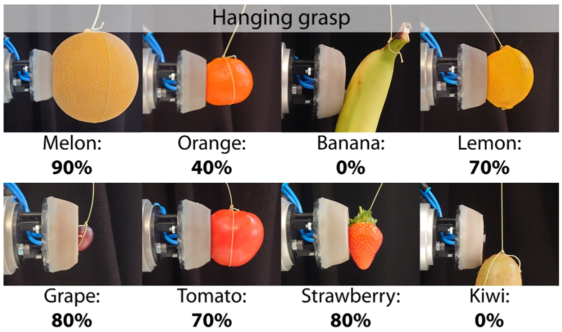


Fig. 9: Grasping results from a hanging position (harvesting) of oranges, grapes and tomatoes.

when picking from a table with 10 trials. A variety of surface textures are seen. Large, smooth, uniform objects are picked securely with 100% success rate (melon, orange and tomato). The textured kiwi is similarly picked with high success rate due to the uniform shape. The packet and grape are both only held by the bellows, the grape being too small for the cup and the packet lacking the structural integrity to maintain a seat with. The banana is similar to the 40 mm curved surface and success is highly sensitive to the localisation of the banana, if there is any offset, the pick is likely to fail. Picking from clutter is possible (orange and lemon).

Fig. 8b shows the softer fruit after picking. Vertical picking applies a significant load to the object, especially when requiring a large deformation to pick. Small indents from the bellows are observed on the banana (high pressing force needed) and tomato (delicate). Significant damage was caused to the strawberry after repeated picks, where the bellows' vacuum pulled away flesh. The remaining fruits displayed little or no damage or marks after grasping.

e) Harvesting: Fruit are suspended to simulate harvesting. Grasping follows the same procedure as previously, though now there is no reaction force to the pressing.

Table II shows the object parameters as well as an estimate of the upper and lower bounds on net pulling force ($F_b - F_p$); based-on (2) and (3). With negative upper *and* lower bound, the banana is certain to fail, which is observed. The orange, tomato, lemon and kiwi are on the borderline and have observably worse grasping success rate when compared to the melon with positive upper and lower bound. The grape and strawberry do not fit into the model, being successfully picked using just the bellows cup. As long as the bellows force (maximum 2.63 N) is significantly greater than the object weight then this is a valid picking mode.

The variance in grasping success is primarily due to misalignment. The grippers initial approach can knock hanging objects away rather than form a seal with the bellows, or the cup deformation needed is too great. In particular, the orange is highly sensitive to misalignment, as small offsets on the small diameter result in a drastic increase in pulling force required with high bellow deflection. The kiwi fails to follow the model predictions in Table II, this is due to the unaccounted hairy textured surface, which increases the pulling force required to make a seal and decreases the bellows pulling force with air leakage.

V. CONCLUSIONS

Overall, our novel suction cup design improves upon other soft grippers, leveraging excellent automatic shape adaptation and the ability to pick with fewer environmental constraints.

We are able to model the behaviours of the bellows and cup to successfully predict grasping performance on a set of benchmarking surfaces. In addition, we demonstrate grasping of real world objects with varied properties—from highly deformable packets to rigid and heavy melons—varied shapes and sizes—individual grapes to non-uniform bananas—and in different environments.

There are a number of improvements possible with this system. Firstly, the grasping model fails to account for surface textures like hairs. Secondly, the current gripper design has limited bellow deflection and force, meaning small diameter object such as oranges have low hanging grasp success. Design optimisation can improve the bellow and cup characteristics to maximise softness during grasp formation, without sacrificing grasp quality or strength. Improving grasping robustness in this way allows for applicability in real-world industrial agriculture or logistic warehouse tasks.

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