A Caging Inspired Gripper using Flexible Fingers and a Movable Palm

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***Abstract*— This paper proposes the design of a robotic gripper motivated by the bin-picking problem, where a variety of objects need to be picked from cluttered bins. The presented gripper design focuses on an enveloping cage-like approach, which surrounds the object with three hooked fingers, and then presses into the object with a movable palm. The fingers are flexible and imbue grasps with some elasticity, helping to conform to objects and, crucially, adding friction to cases where an object cannot be caged. This approach proved effective on a set of basic shapes, such as cuboids and cylinders, in which every object could be grasped. In particular, flat bottom parts could be grasped in a very stable manner, as demonstrated by testing grasps with multiple 5N and 10N disturbances. A set of supermarket items were also tested, highlighting promising features such as effective grasping of fruits and vegetables, as well as some limitations in the current embodiment, which is not always able to slip the fingers underneath objects.**

I. INTRODUCTION

Grasping items with a robotic gripper is a vital part of automated production processes and robotics in the modern era. There are a huge variety of robotic grippers in industry, reviewed in [1], most of which are specialised to their task and designed with specific objects in mind. A key challenge is to propose designs for more universal grippers, able to handle a wide variety of objects.

Some designs have been inspired by the human hand, the foremost exemplar of a universal gripper, and have achieved comparable degrees of actuation [2], [3]. However, controlling such complex hands remains a challenge. In contrast, other designs aim for simplicity, letting fingers conform to an objects shape using underactuation [4]–[9]. The drawback of this simplicity being that the variety of grasps is limited. Consequently, many commercially successful designs which offer grasping for a variety of objects occupy a design space termed “medium complexity” [10], with three to five degrees of actuation, for example the Barrett Hand, Robotiq 3-Finger Gripper, and Kinova Jaco Hand.

This paper investigates the design of a new medium complexity gripper with three actuators, shown in Figure 1. The gripper has three fingers, each capable of two Degrees-of-Freedom (DoF) motion and all driven together by two motors. These fingers have two key design elements: firstly, they are long and flexible cantilevers; secondly, they feature a 90 degree bend which aims to hook behind objects.

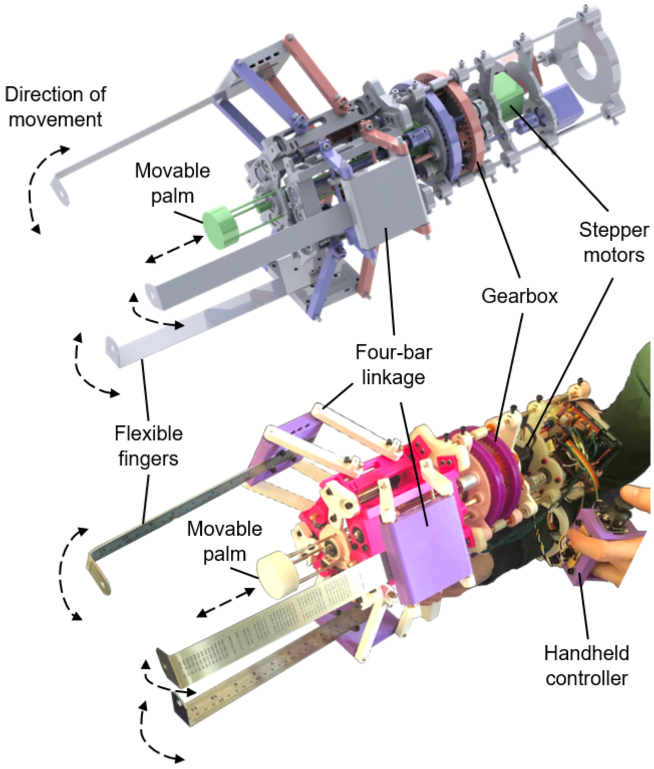

Fig. 1. CAD illustration and prototype of our proposed gripper; the movable palm can constrain objects and press them into the fingers.

This research is motivated by the bin-picking problem, where assorted random objects are chaotically piled in a bin, and require picking and sorting by an automated process. This is a complex problem to solve, with applications in warehouses, logistics, and shipping; popular use case examples being Ocado and Amazon. It requires a gripper than can pick and place a large variety of objects reliably whilst dealing with clutter. This paper proposes that a design combining caging and force closure may offer simple and reliable grasping of a variety of objects. Caging refers to placing a constraints around an object to prevent it escaping grasp, whilst force closure relies on friction like in a two-finger pinch, as with parallel-jaw grippers.

Many contemporary hand designs rely on fingers curling behind an object, then dragging it into the palm. In contrast, the idea here is to directly place the fingers behind an object and move the palm forwards to meet it, pressing the object into those fingers and creating a stable grasp. The fingers and palm act as barriers to cage objects, and then friction is introduced by squeezing the object between the fingers and

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palm to immobilise it. By making the fingers flexible, the resulting grip is both more versatile and easier to control, since the force exerted is a function of the finger stiffness.

The novelty presented in this paper stems from combining this caging inspired movable palm and flexible fingers approach to grasping. The goals of this work are to demonstrate proof of principle for this design and to validate that effective grasps can be achieved on a variety of objects. Sets of elementary objects and supermarket items were tested to determine the effectiveness and versatility of the gripper.

The rest of the paper is organized as follows. Section II details related work, while in Section III the gripper design is explained. Experimental methods are given in Section IV, followed by results and discussion in Section V. Finally, conclusions are discussed in Section VI.

II. RELATED WORK

The motivation for this work overlaps with the concept of a cage, which has often been studied from a mathematical perspective. As discussed, a cage introduces geometric constraints around an object, removing paths the object could take to escape the manipulator. It is a bound on mobility which still allows the object to move within the grasp. A review of caging for robotic applications is given in [11]. To summarise, caging in 3D is an unsolved problem which is highly complex, and so most research, including for grippers, focuses on 2D and 2.5D cases [12], [13]. Rodriguez et al. [14] discussed the role of caging in grasping and its usefulness for pre-grasping poses. This is similar to the approach taken in the current work, the gripper is designed to surround the object and prevent escape as the grip closes.

Previous works using caging grasps often treat fingers as frictionless rods with binary actuation, as this is easier to model. For example, caging grasps for polyhedron-like workpieces were computed from images and executed by a four-pin binary gripper in [15]. Mason et al. [16] used a three-pin binary gripper for bin-picking marker pens, not with caging but by sweeping the fingers in from behind, as in the style of this paper. Both these works relied on objects tending towards stable poses as they are grasped, illustrating that caging-like grasps can be error-tolerant and effective with minimal sensing. The present design also employs simple fingers, but introduces flexibility to aid grasping.

Egawa et al. [17] explored caging with flexible elements, presenting their concept of caging-based grasping and defining it mathematically. This involved a rigid skeleton caging the object and softer urethane foam "flesh" cushioning against it. The design in this paper is akin to combining the skeleton and soft parts into one jointless, flexible finger and adding a movable palm; then, operating with a less rigorous approach where objects are not always caged.

Introducing compliant or "soft" elements into grippers has also been widely studied. Deimel and Brock [18] produced a dexterous robotic hand made almost entirely from silicone; meanwhile, compliance has been used for entire fingers [19], for finger joints [20], or introduced into a rigid finger structure with elastic tendons [6]. Compliant elements aid delicate handling by limiting the maximum exertable force in a grip, and in a similar manner grant shock resistance and conformance to objects. All these benefits are realised by our presented design, however by using steel instead of silicone some key drawbacks of compliance are addressed; cantilever fingers are simpler to model, instrument, and easier to modify for controlling properties like stiffness.

A commercial gripper, the Righthand Robotics RightPick, also uses three compliant fingers, and has a movable vacuum cup which extends out of the palm. It uses suction to secure and lift objects, then engages the fingers to stabilise it afterwards. Our present design shares a similar hand structure, but differs in grasping approach. The two DoF fingers with hooks and barrier palm aim to lead with the fingers and cage objects. This avoids the need for suction, which is already a proven technology is warehouses and logistics domains.

Since caging is extremely geometry dependent, the current work aimed to validate on a set of elementary objects. A possible use-case for a caging style gripper may be automated food delivery packing. Most supermarket items could be described as elementary shapes, cylinders or boxes, since they need to densely pack during shipping. A benchmark for pick-and-place systems was proposed by Mnyusiwalla et al. [21] in the context of grocery handling. They characterised this dense packing as a key challenge, as robots may need to extract food from cluttered or tightly packed containers. Grippers with long and thin fingers based around caging may offer one solution to this problem due to excellent reach and the potential to slip between packed objects.

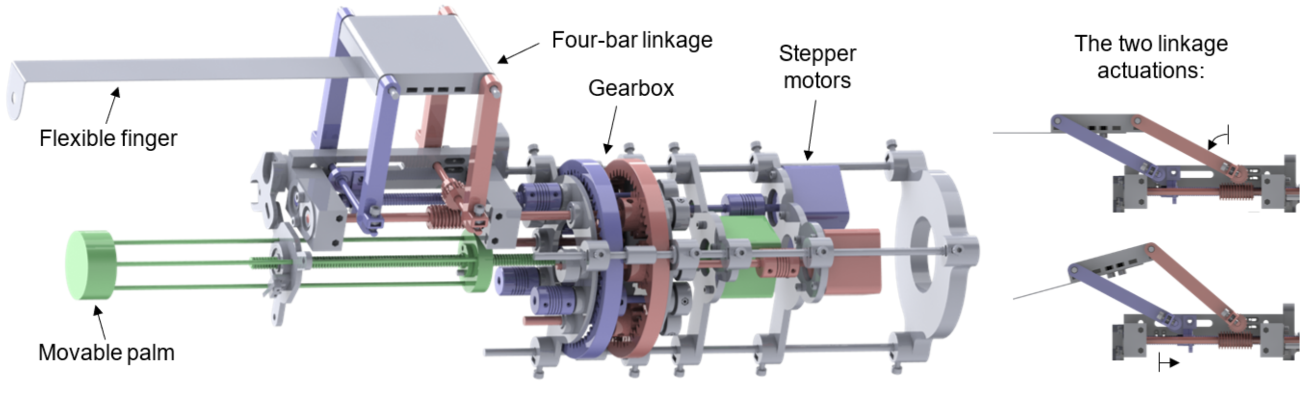
III. DESIGN

The gripper was designed with proof of concept in mind. Therefore, some features were intentionally excluded, such as coating the fingers and palm in high friction material. Additionally, limited access to resources during the pandemic meant that most parts should be cheaply 3D printed. The key elements of the design are shown in Figure 2-a).

A. Finger Design

The idea behind the grasping was to combine a caging style approach with a tight grip that relied on friction. The fingers should hook behind an object as the palm moves in from above to prevent the object escaping. This is the first stage, based on caging. Next, the palm and fingers should squeeze the object in grip to tightly secure it. The flexibility of the fingers helps to achieve this; when the palm presses the object the fingers are flexed and loaded like springs to exert force on the object. The stiffness of the fingers controls the force exerted in the grip, and their flexibility allows them some room to conform to objects.

Therefore, these fingers were simply steel cantilevers with a 90 degree right angle bend in the end, henceforth referred to as the hook. 30cm metal rulers were used, 0.9mm thick and 28mm wide, due to their ease of purchase and ideal size. In keeping with the aim for simplicity and proof of concept, the hooks and finger stiffness were left 'as is', not optimised for their role of slipping under and constraining objects.



(a) (b)

Fig. 2. (a) Key design elements; colour coding is used to distinguish which parts are driven by which motor. (b) Linkage actuations.

B. Finger Actuation

In order to enable fingers to get behind objects and cage then, 2 DoF actuation was chosen. The fingers needed to be able to spread out and constrict, as well as tilt to scoop objects up. These two motions were achieved with a four bar linkage, as shown in Figure 2-b).

The rear strut in the linkage has its angle controlled by a worm drive, which achieves high gear reduction and importantly, is non-backdriveable, so the finger presents a barrier to the object. Changing the angle of this rear strut leans the linkage forwards, resulting in finger moving towards the centre of the grip. The front strut in the linkage has its displacement controlled by a leadscrew, which is similarly non-backdriveable. Changing the displacement of this front strut tilts the finger through different angles. The amount of angular change depends on the shape of the linkage; more tilt can be achieved when the linkage is leaning forwards.

Each of the three fingers is therefore actuated in two degrees of freedom and controlling them all separately would require six motors. Instead, the motions of each finger were directly coupled so they would move identically and only two motors would be needed. This means the resultant grip is symmetrical, which does place limits on which objects can be caged, but this should be partly compensated for by the flexibility of the fingers.

C. Palm Actuation

Actuating the palm is important not only for caging objects, but also for squeezing them tighter in the grip. A leadscrew was chosen to actuate the palm, since large displacement non-backdriveable linear motion was required. This leadscrew ran down the centre of the gripper, so all the other mechanisms needed to be designed around it.

There is scope for modifying such a palm, perhaps to include another means of securing the object, such as cushioning or a granular jamming device. However, for this initial design a flat surface is used to demonstrate proof of concept. Despite not adding elastic elements to the palm, elastic behaviour is already present in any grip due to the flexibility of the fingers.

D. Drive Arrangement

Stepper motors were chosen for all three actuations, due to their simple open-loop position control. Nema 17 motors were used, two Kysan 1124090 550mNm motors for the fingers and one Usongshine 420mNm motor for the palm.

In order to drive all three fingers from only two motors, the single drive shaft of each motor would need to be transformed into three identical outputs, one for each finger. A gearbox was chosen to accomplish this, using ring gears which also leave space for the leadscrew driving the palm. Each motor drives a large ring gear via a spur gear. This ring gear in turn spins three other gears, each connected to shafts driving the motion of the fingers. Since there were two motors driving the fingers, two ring gears were needed with four internal gears each. Due to the circumstances, all these gears were 3D printed, which introduced issues of size, tolerance and vibration. The large size and 4.5kg final weight of the prototype were permissible for its role in proof of concept, whilst tolerance and vibrational issues were addressed with flexible shaft couplers and motor microstepping.

IV. EXPERIMENTS

Two types of experimental methods were performed to validate the design. Firstly, testing with a set of basic shapes, such as spheres, cubes, and cylinders. This experiment evaluated the quality of grasps using three disturbances. Secondly, an experiment on a variety of supermarket objects to demonstrate the versatility of the gripper.

The first experiment took place on a set of 18 objects: six basic shapes were chosen, and a small, medium, and large example was used for each. Small was defined as around the lower limit the gripper was capable of grasping, whilst large was the upper limit. An overview of all the objects is given in Figure 3, with the names and dimensions in Table I.

The first experiment aimed to determine which basic shapes can be grasped, and evaluate how stable these grasps were against disturbances. An experienced human operator held and operated the gripper, positioning the fingers correctly relative to the object and activating the motors to obtain a grasp from above. Flat bottomed objects were

TABLE I

DETAILS OF 18 OBJECTS USED FOR EXPERIMENT ONE, INCLUDING DIMENSIONS (DIM.)

Object Size	Object Details	Sphere	Cylinder Sideways	Cylinder Upright	Cube	Cuboid Flat	Cuboid Upright
Small	Name	Pink ball	Anchovy jar	Glass jar	White cube	Electronics box	Blue box
	Dim. (mm)	r = 60	d = 47; h = 84	d = 66; h = 84	l = 50	l = 128; w = 95; t = 18	l = 105; w = 80; t = 28
	Mass (g)	30	180	180	42	10	13
Medium	Name	Purple ball	Biscuit tin	Black tin	Colour cube	Oil paint box	Multimeter box
	Dim. (mm)	r = 100	d = 65; h = 260	d = 75; h = 150	l = 100	l = 240; w = 110; t = 20	l = 162; w = 160; t = 50
	Mass (g)	100	105	104	304	32	57
Large	Name	Red ball	Yellow tin	Tea tin	Metal cube	Delivery box	CX430 box
	Dim. (mm)	r = 140	d = 185; h = 175	d = 165; h = 175	l = 155	l = 260; w = 100; t = 100	l = 260; w = 186; t = 95
	Mass (g)	209	401	370	496	50	179

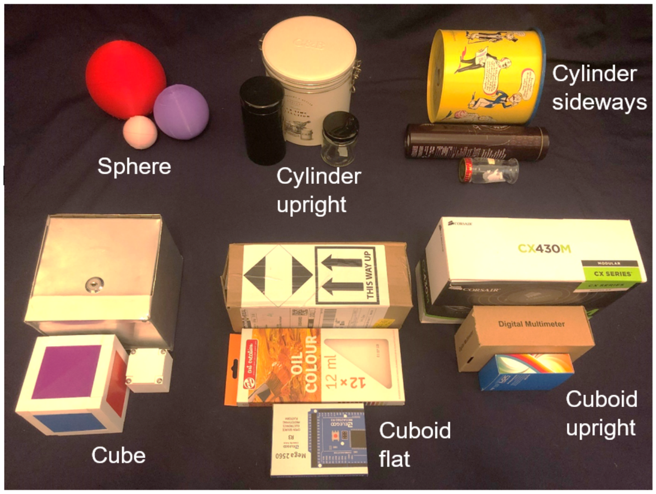


Fig. 3. The six types of object used for experiment one, with three examples of each: small, medium, and large.

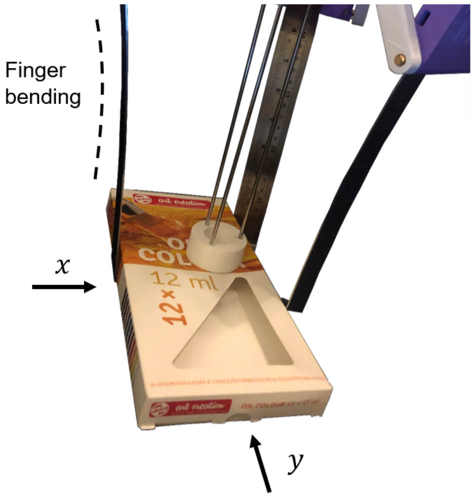


Fig. 4. Demonstrating a grasped object, and the disturbance directions. Disturbance x will be opposed by two fingers, y by zero - it isn't caged.

mounted on stands to allow the fingers to slip underneath easily; the reason for this is that this experiment should assess the quality of the grasp not the ease of grasping, that is tested in the second experiment.

The operator attempted to grasp each object 10 times in a row following some initial practice. Attempts started once any object contact was made, and any break in contact or need to re-grasp constituted failure. Attempts leading to successful grasps were then assessed for stability by applying two disturbances to the object, named x and y. These were both perpendicular to gravity. x was always in the direction that the grasp was most stable, and y in the direction the grasp was least stable, demonstrated in Figure 4. A force of 5N was applied for each using a spring. This force was chosen as it will deflect one finger more than the 35mm hook length, enough to remove the finger from grasp. The disturbance was considered successfully rejected if the object remained in the grasp. Then, the object's mass was increased and the above procedure repeated for another 10 grasps. The mass increases were $0.3 - 0.5$kg for the small objects[1] and exactly 1.0kg for the medium and large objects. These corresponded to a new disturbance, called z, of $3 - 5$N or 10N. The number of successful grasps in each condition and the number of disturbances rejected were recorded for each of the 18 objects.

The objective of the second experiment was to explore the space of graspable objects, testing the gripper on a variety of supermarket items. In this test, objects were simply placed on a hard floor and the objective was to pick them up and place them in a different location. Grasp attempts were defined as in experiment one. This was a qualitative test, so measured disturbances were not applied, but objects needed to survive the gripper shaking and moving. This experiment was performed on 12 objects which are detailed along with the results in the following section.

Both experiments can be seen in the supplementary video.

V. RESULTS AND DISCUSSION

The first experiment tested whether a variety of 18 basic shapes could be grasped, and whether these grasps were stable enough to reject x and y disturbances. The results are shown in Table II for the 10 normal grasps of each object, and 10 grasps with added z weight.

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[1] 0.5kg would not fit inside the following three small objects: instead the pink sphere used 300g, the anchovy jar 335g, and the white cube 418g.

TABLE II

RESULTS FROM EXPERIMENT ONE, EACH FIELD IS SCORED OUT OF 10 GRASP ATTEMPTS

		Small			Medium			Large		
		Grasped	Resist x	Resist y	Grasped	Resist x	Resist y	Grasped	Resist x	Resist y
Sphere	Normal	6	5	4	10	7	5	10	9	4
	With z	8	0	0	6	0	0	8	0	0
Cylinder upright	Normal	10	10	8	10	10	10	10	10	10
	With z	10	6	2	10	10	10	10	10	10
Cylinder sideways	Normal	10	9	1	10	10	3	10	10	10
	With z	10	8	0	3	0	0	8	7	0
Cube	Normal	8	7	4	10	10	10	10	10	10
	With z	9	7	6	10	10	9	10	10	10
Cuboid upright	Normal	10	10	10	10	10	10	10	10	10
	With z	10	10	10	10	10	10	10	10	10
Cuboid flat	Normal	10	10	10	10	10	10	10	10	10
	With z	10	10	9	10	10	10	10	10	10

The first important result is seen from the grasping success rates of the objects. Without added mass, only the sphere and cube had failed grasps. This is because they were so small that they could slip between the closed fingers of the gripper. Interestingly, in both cases added mass improved the situation, since the heavier objects had more inertia and slipped and rolled less.

The larger spheres and sideways cylinders experienced failed grasps when mass was added. In general, these were the objects which had the most unstable grasps, accounting for all the occurrences of zero disturbance rejection in Table II. These objects did not have flat bottoms, and consequently the finger hooks tended to slide and scrape against the surface without getting a good grip. This resulted in low friction, which explains the poor ability of the spheres and sideways cylinders to resist y disturbances. For caged objects, the y disturbance is resisted by one finger, for non-caged objects it is resisted by zero fingers, as in Figure 4. In both cases friction is needed to help resist the 5N force.

The medium and large sphere could both be caged by the gripper, and yet did no better than the sideways cylinders, which could not be caged. The reason for this is that the finger stiffness was too low; the caging fingers were pushed aside when mass was added to the spheres.

Moving on to the remaining objects with flat bottoms, aside from some issues with the smallest objects, the performance of the grasps was very consistent. The success comes down primarily to friction. Similar to the sideways cylinder, the cuboids could not be caged. Hence, if the grip were frictionless none could have resisted the y disturbance. Instead, the opposition created between the palm and the finger hooks was effective for generating friction and the tightness of the grip was easily controlled by adjusting how much the palm pressed on the object. When the palm pressed on an object, the fingers began to bend, storing elastic energy, as illustrated in Figure 4. This resulted in an easily controlled gripping force, sufficient to reject the 5N y disturbance.

In summary, there were two mechanisms in the grip. The cage, which relied on the finger stiffness and object geometry, and the friction. These results show that caging grips were weak without friction, like those for larger spheres. They also show that friction grips were strong independent of caging, as for the cuboids. However, it is important to note that caging grips on rounded bottom objects were still effective at grasping and could be improved with stiffer fingers. Qualitatively, it was noted that these grips did resist lower x and y forces such as 3N, instead consistently failing as the spring approached 5N.

The second experiment illustrated the capability of the gripper on 12 different supermarket items. 10 grasps were attempted on each, with the results given in Figure 5. No aids for grasping were given; the objects lay on the floor rather than on stands. The results show that the gripper performed well when it was able to get its fingers under objects, for example rounded bottom objects such as the lemon, bell pepper, and cucumber. With the exception of the sideways tin, these objects were of low weight and thus simple to grasp, supporting the good grasping success rates from experiment one. The lemon outperformed the similarly sized pink ball from experiment one since it rolled less and has a higher friction surface; this is evidence that grasping results would be improved by using high friction surfaces on the fingers and palm.

The flat bottomed objects had worse results, despite being very stable once gripped, for example the milk carton, which was the heaviest object at 1.3kg. For the tomato jar and the milk carton, grasps were successful half the time, depending on if the fingers could slip underneath. Meanwhile the upright tin and passata could not be grasped, illustrating the main limitation of the finger design, which

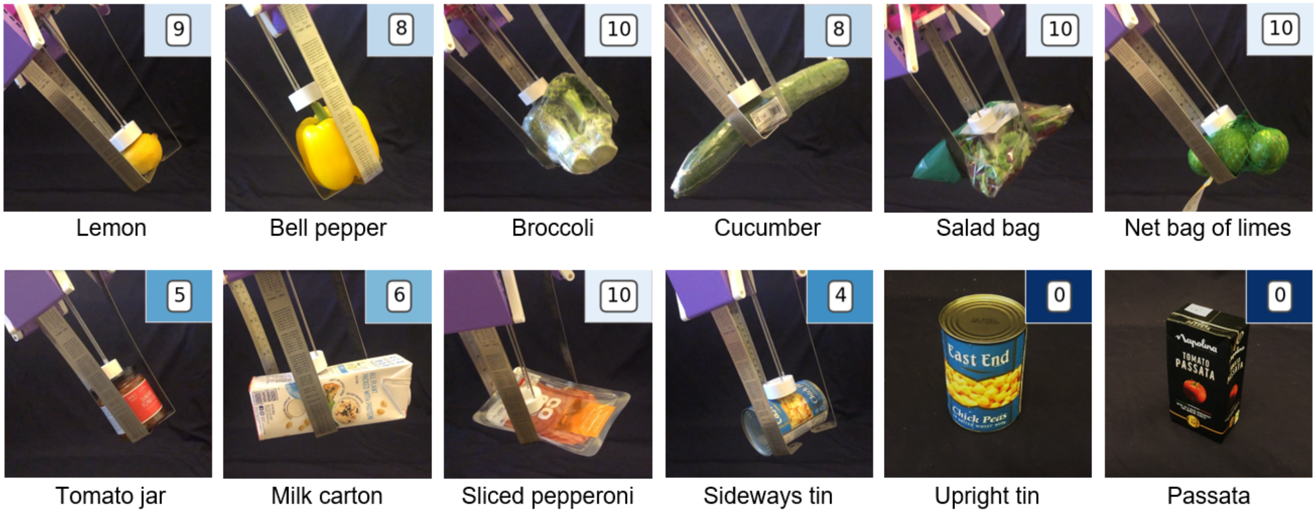

Fig. 5. Results from experiment two, each of the 12 supermarket items are labelled with the number of successful grasps out of 10 attempts.

requires hooking under objects. The sliced pepperoni fared well, demonstrating how this gripper can perform well on objects that hand shaped grippers would struggle with; even a human would struggle to lift this item from the top.

VI. CONCLUSION

We presented a design for a caging inspired gripper; key elements being a movable palm and long, flexible fingers. Grasps were demonstrated on every elementary shape in the first experiment, being stable on flat bottom objects, where friction dominated, but demonstrating poor disturbance rejection in cases like the sphere, where caging dominated.

The second experiment highlighted some practical strengths and weaknesses of the design. The gripper struggled to slip its fingers under flat bottomed objects, but coped well with fruit and vegetable items and is well suited for controlling the force in a grip by exploiting the opposition of the palm and flexible fingers.

Future iterations and testing of the proposed design would focus on evaluating the benefits of design adjustments to increase finger and palm friction, as well as finger stiffness to improve stability of caging dominated grasps. Improving finger hook design could improve their ability to slip under objects, and overall size and weight reductions are needed.

REFERENCES

[1] G. Fantoni *et al.*, "Grasping Devices and Methods in Automated Production Processes," *CIRP Annals - Manufacturing Technology*, vol. 63, no. 2, pp. 679–701, 2014.

[2] S. Jacobsen, E. Iversen, D. Knutti, R. Johnson, and K. Biggers, "Design of the Utah/M.I.T. Dextrous Hand," in *IEEE International Conference on Robotics and Automation*, vol. 3, pp. 1520–1532, 1986.

[3] M. Grebenstein *et al.*, "The hand of the DLR hand arm system: Designed for interaction," *International Journal of Robotics Research*, vol. 31, no. 13, pp. 1531–1555, 2012.

[4] C. Gosselin, F. Pelletier, and T. Laliberté, "An Anthropomorphic Underactuated Robotic Hand with 15 DoFs and a Single Actuator," in *IEEE Int. Conf. on Robotics and Automation*, pp. 749–754, 2008.

[5] A. M. Dollar, L. P. Jentoft, J. H. Gao, and R. D. Howe, "Contact Sensing and Grasping Performance of Compliant Hands," *Autonomous Robots*, vol. 28, no. 1, pp. 65–75, 2010.

[6] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive Synergies for the Design and Control of the Pisa/IIT SoftHand," *International Journal of Robotics Research*, vol. 33, no. 5, pp. 768–782, 2014.

[7] D. Kanoulas, J. Lee, D. G. Caldwell, and N. G. Tsagarakis, "Visual Grasp Affordance Localization in Point Clouds Using Curved Contact Patches," *IJHR*, vol. 14, no. 01, p. 1650028, 2017.

[8] D. Kanoulas, J. Lee, D. G. Caldwell, and N. G. Tsagarakis, "Center-of-Mass-Based Grasp Pose Adaptation Using 3D Range and Force/Torque Sensing," *IJHR*, vol. 15, no. 04, p. 1850013, 2018.

[9] J. Gomez-de Gabriel and H. Wurdemann, "Adaptive Underactuated Finger with Active Rolling Surface," *IEEE Robotics and Automation Letters*, 2021.

[10] N. Ulrich, *Grasping with Mechanical Intelligence*. Phd thesis, University of Pennsylvania, 1989.

[11] S. Makita and W. Wan, "A Survey of Robotic Caging and its Applications," *Adv Robot*, vol. 31, no. 19-20, pp. 1071–1085, 2017.

[12] E. Rimon and A. Blake, "Caging 2D Bodies by 1-parameter Two-Fingered Gripping Systems," in *Proceedings of IEEE International Conference on Robotics and Automation*, vol. 2, pp. 1458–1464, 1996.

[13] A. Sudsang, J. Ponce, and N. Srinivasa, "Grasping and In-Hand Manipulation: Experiments with a Reconfigurable Gripper," *Advanced Robotics*, vol. 12, no. 5, pp. 509–533, 1997.

[14] A. Rodriguez, M. T. Mason, and S. Ferry, "From Caging to Grasping," *Int J of Robotics Research*, vol. 31, no. 7, pp. 886–900, 2012.

[15] J. Su, H. Qiao, Z. Ou, and Z. Y. Liu, "Vision-Based Caging Grasps of Polyhedron-Like Workpieces with a Binary Industrial Gripper," *IEEE Transactions on Automation Science and Engineering*, vol. 12, no. 3, pp. 1033–1046, 2015.

[16] M. T. Mason, A. Rodriguez, S. S. Srinivasa, and A. S. Vazquez, "Autonomous Manipulation with a General-Purpose Simple Hand," *Int J of Robotics Research*, vol. 31, no. 5, pp. 688–703, 2012.

[17] T. Egawa, Y. Maeda, and H. Tsuruga, "Two- and Three-Dimensional Caging-based Grasping of Objects of Various Shapes with Circular Robots and Multi-fingered Hands," in *IEEE Industrial Electronics Society*, pp. 643–648, IEEE, 2015.

[18] R. Deimel and O. Brock, "A Novel Type of Compliant and Underactuated Robotic Hand for Dexterous Grasping," *International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 161–185, 2016.

[19] H. K. Yap, H. Y. Ng, and C. H. Yeow, "High-Force Soft Printable Pneumatics for Soft Robotic Applications," *Soft Robotics*, vol. 3, no. 3, pp. 144–158, 2016.

[20] L. U. Odhner *et al.*, "A Compliant, Underactuated Hand for Robust Manipulation," *International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, 2014.

[21] H. Mnyusiwalla *et al.*, "A Bin-Picking Benchmark for Systematic Evaluation of Robotic Pick-and-Place Systems," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 1389–1396, 2020.