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The Double-Scoop Gripper: A Tendon-Driven Soft-Rigid End-Effector for Food Handling Exploiting Constraints in Narrow Spaces

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***Abstract*— Food handling is a challenging task for robotic grippers, as it requires to manipulate highly deformable and fragile items, that can be easily damaged. Moreover, ingredients for the preparation of the different dishes are usually stored in small containers that are often not easily accessible. This paper introduces an innovative soft-rigid, tendon-driven gripper: the Double-Scoop Gripper (DSG). Its two-fingered design exploits a specialized structure to cope with constrained spaces (e.g., containers in narrow shelves). The DSG can delicately grasp objects of various shapes by employing two scoop-shaped fingertips that can form a single plate when fingers are flexed. Data obtained from an on-board camera are used to detect the food item features and plan the grasping strategy that better exploits the possible environmental constraints regulating the opening of the two fingers and the approaching direction of the gripper. DSG capabilities are verified with experiments conducted using real food ingredients within a pick-and-place setup to evaluate both the grasping and the releasing capability of the gripper. Obtained results are promising and suggest that this approach could be particularly advantageous in the context of automated food serving.**

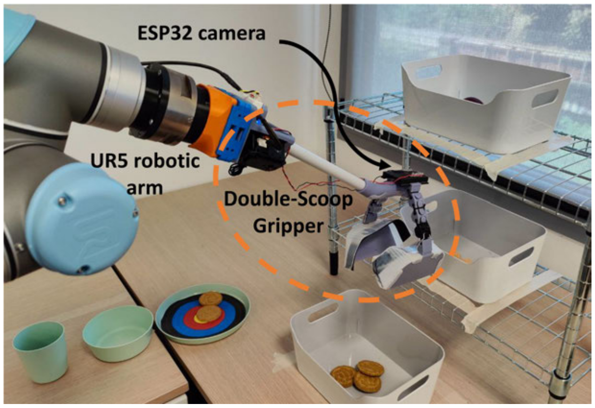

Fig. 1: Experimental setup for food handling. Pick area: 3 containers at different heights (table, within and above the shelves). Place area: 3 containers of varying sizes (plate, bowl, glass). The proposed Double-Scoop Gripper, embedding an on-board camera, is indicated with an orange circle.

I. INTRODUCTION

Food manufacturing has witnessed significant advancements in automation and robotics, revolutionizing food handling processes. In this context, industrial food service robots play a pivotal role in enhancing efficiency, conserving space, and elevating cleanliness and safety standards [1]. Over the past few decades, robotics found widespread usage in tasks like dispensing ingredients, executing precise cuts, packaging or casing food items, as well as skillfully picking and placing products into containers while also facilitating the sorting process [2], [3]. Food handling is an important task also in assistive applications in which robot manipulators can be used to help people in the kitchen or feed and serve patients with upper limb impairments [4], [5].

When dealing with pick-and-place tasks, robotics must face three main challenges [6], [7]. To begin with, the robot end-effector must delicately handle the fragile nature of food items susceptible to damage. Secondly, the robot capability to adjust to environmental changes is crucial, ideally without necessitating a reconfiguration of the entire robotic setup. Lastly, vision algorithms are vital in detecting and recognizing the targeted food items for picking. However, complexities like obstacles within the scene often obstruct a clear view of the workspace.

In this work, we propose the development and application of a novel soft-rigid gripper, the Double-Scoop Gripper (DSG), specifically designed for pick-and-place scenarios (as shown in Fig. 1). The gripper was devised to tackle the food tray assembly scenario of the *2023 IEEE Robosoft Competition ("food handling for trays preparation")* [8], where food was stored in containers placed in restricted spaces (i.e., containers in narrow shelves) and needed to be released into small containers like bowls and plates. The gripper structure comprises two opposing tendon-driven soft fingers. Exploiting the idea of "side and bottom grasp" defined in [6] and introduced in [9], we positioned at the tips of these fingers a flat, rigid component able to slide below the food items with additional flexible borders that create a scoop (Fig. 1). This unique configuration offers a threefold advantage: firstly, it allows the gripper to cage objects rather than applying conventional pinching; secondly, it improves the releasing of the food items with respect to other soft grippers; lastly, it enables the gripper to grasp the food exploiting the constraints present in the environment (e.g., other food items or container walls) [10]. To cope with narrow environments, the gripper palm is attached to the

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robot arm end-effector through a rigid support element. This feature allows us to manoeuvre the gripper into constrained spaces where it is not possible to perform top grasps. The finger actuators and the electronics for low-level control are positioned at the robotic arm end-effector making the gripper part that may be in contact with the food completely washable. The repositioning of the motors also decreases the bulkiness of the gripper which represents an important feature when grasping in narrow spaces.

An RGB camera is embedded in the palm of the gripper. This placement ensures the identification of objects inside containers, even when obstructive elements like shelves or other containers occlude the visual field of an external camera. To determine the features of the objects, we employed a vision algorithm that first acquired the camera images and consequently planned the grasping strategy that better exploited the possible environmental constraints. Then, depending on the position and the size of the food items, the opening of the fingers and the gripper orientation were regulated to adapt to the exploitable environmental constraint.

The proposed gripper was tested evaluating the grasping and releasing success rate in a scenario with real ingredients in multiple containers and a tray, considering single and multiple objects pick-and-place operations.

II. RELATED WORKS

The design of grippers for food handling requires careful considerations due to the wide variety of shapes, textures, and weights that food items can have, as well as the unstructured nature of the environments where they are stored. Grippers based on suction cups are extensively used in the food industry due to their affordability and ease of use [11]–[13]. They guarantee swift operations in food handling systems to ensure production efficiency, and are optimal when picking products with uneven surfaces. However, suction cups cannot accomplish certain handling tasks involving moist and porous food materials. Alternatively, targeted solutions for moist food were investigated in [14] and [15], where the authors presented devices exploiting adhesion forces and modifying the thermal characteristics of the objects (e.g., freezing the moist surface), respectively.

A significant aspect to address pertains to the vulnerability of food items to potential damage. Given this inherent fragility, various technological approaches have emerged over time, each carrying its own set of advantages and disadvantages. The airflow vacuum tool [16], [17], and the grippers based on Coanda effect [18] or Benoulli's principle [19] do not require direct contact with food, and are ideal for fragile items. Nevertheless, these working principles present limited payload depending on the available surface of the objects.

Grippers with soft fingers represent a viable trade-off between managing fragile objects and conforming to their shape. For instance, in [20], the authors present a monolithic soft gripper capable of adapting to objects thanks to a process of design optimization. However, dealing with food, it is fundamental that grippers possess modularity, facilitating swift cleaning and replacement of components for manufacturers.

Regarding the actuation mechanisms, the prevailing technologies are pneumatic [21]–[24] and cable-driven fingers [9]. In [22], the authors present a soft actuator molded only from silicon rubber, while Yamanaka et al. [23] demonstrate the effectiveness of using pre-stressed pneumatic fingers to be able to grasp several food items without damaging them. The majority of these grippers approaches the food items from the top surface, but when dealing with very fragile items the likelihood of risk of food damage is very high.

Handling food products from the bottom surface can be a viable alternative strategy. Besides, it is a method widely adopted by humans (e.g., using a spatula for cooking foods). However, in literature, there are very few grippers [9], [25], [26] that exploit this type of solution. In [9], the authors show that inserting passive magnetic nails at the last phalange improved the grasping success rate and reduced the damage done to food. Similarly, a paper-like gripper is presented in [25], wrapping the objects without damaging them.

As demonstrated in [27], [28], the concept of sliding between the object and a part of the environment becomes more important when dealing with restricted scenarios, like a food container. For these reasons, we decided to design the gripper with soft-rigid fingers and scoops at the fingertips, to be able to adapt to the environment and consequently to slide beneath the objects. The authors of [29], [30] also increased the dexterity of the robot, introducing additional degrees of freedom in the wrist design. In our work, this was not possible because we placed the motors for the tendon-driven actuation of the gripper at the robotic arm end-effector to reduce the encumbrance of the device and guarantee the complete washability of the parts in contact with the food.

III. METHODOLOGY

A. Gripper Design

The design of the Double-Scoop Gripper complies with the two following guidelines: *i*) prevent damage to delicate food, and *ii*) grasp items placed in narrow places. We developed this gripper accounting for the food tray assembly scenario considered in the *2023 IEEE Robosoft Competition*. The CAD of the DSG is shown in Fig. 2. The core components of the gripper are the two scoops placed at the fingertips. When closed, they form a flat base that can be slid under food items, becoming extremely useful to avoid damages. The two scoops have a surface area of $60\,\mathrm{cm}^2$ each. We also added soft protection walls to the three sides of the scoop to force the food to stay on the gripper base.

Another important feature of our design is the use of two motors (one per finger) for the tendon-driven actuation. This solution helped in connecting the two scoops to the motor housing using a rigid plastic pipe characterized by a length of $20\,\mathrm{cm}$. To actuate the soft-rigid structures that drive the motion of the scoops and to redirect the path of the tendons, we design a unique structure, highlighted in Fig. 2. This part of the gripper was shaped to reduce the friction on the tendon by having a smooth curved channel with a large curvature radius, thus avoiding the addition of two pulleys.

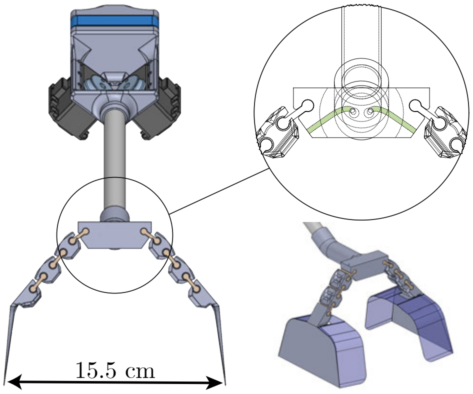


Fig. 2: CAD design of the Double-Scoop Gripper.

All these design features allowed us to significantly reduce the gripper bulkiness, making it possible to grasp objects in narrow spaces. The position of the two actuators and the electronics at the robotic arm end-effector makes the parts of the gripper washable.

All the rigid parts, consisting of the motor housing, the motor pulleys, the tendon router part, the rigid modules of the scoops and the scoop base, are made with Elegoo ABS-like resin, except for the tube, which is a commercial PVC tube. All the flexible parts, the flexible hinges and the food protector around the base are made of 85A shore TPU. We used two Dynamixel MX-28AT motors controlled by an ESP32 microcontroller connected to a custom transistor-transistor logic adapter board.

To measure the payload of the gripper, we closed it in such a way to form a flat surface with the two scoops and progressively added weight over them. We stopped as soon as a gap between the scoops started to appear. The resulting gripper payload is 650 g.

B. Object Detection with ESP32-Camera

Another key feature of the DSG is the small RGB camera placed in its palm. This camera allows to detect objects inside food containers even if the hand or other obstacles are occluding the field of view of an external camera. We employed the on-board camera mainly to detect how many objects are present, and where they are with respect to the center of the food container. Once these pieces of information are obtained different grasping strategies can be adopted depending on the objects position and quantity.

The camera we chose is a ESP32-Camera with a resolution of 1280×1024, connected through WiFi to our network. To acquire the images from the ESP32 we used a Real Time Streaming Protocol (RTSP) and we integrated it in ROS with the OpenCV VideoCapture Module [31]. After having obtained the camera image topic (Fig. 3a), we calibrated the camera evaluating its intrinsic parameters. Then, we applied the following steps to detect and evaluate the position of the objects in the scene: ***[Step 1]*** We removed the image background converting the RGB image into the HSV colorspace (Fig. 3b) and thresholding with a filter (Fig. 3c). ***[Step 2]*** Objects contours were obtained by applying a Canny Edge Detection algorithm to find the pixels belonging to the objects edges. Then, another algorithm retrieved the contours from them (Fig. 3d). To improve the algorithm performance we first removed the noise in the image with a 7x7 Gaussian filter. ***[Step 3]*** We extracted the image blobs by labeling the different contours, we evaluated their convex hull, and we kept the ones whose area was larger than an empirical threshold, meaning that they were effectively objects and not noise, as shown in Fig. 3e. ***[Step 4]*** We determined the objects minimum bounding box (Fig. 3f) using the principal component analysis (PCA). ***[Step 5]*** Lastly, we converted the position of the objects from pixels to meters given the intrinsic parameters and the height of the camera.

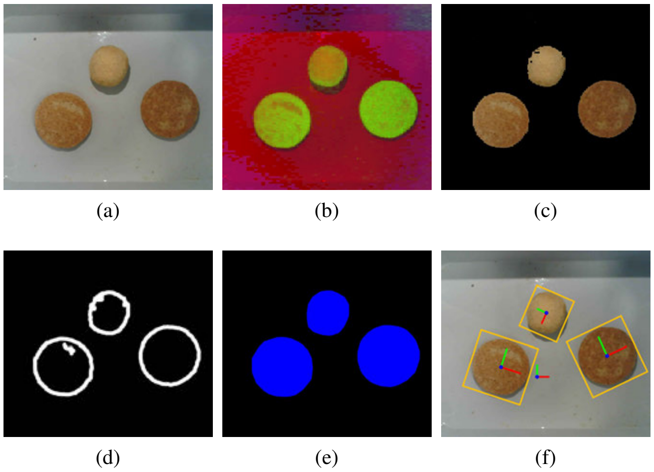

(a) (b) (c)
(d) (e) (f)

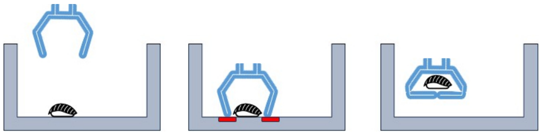
Fig. 3: Detection of food items in containers: a) RGB streaming, b) HSV conversion, c) background removal, d) extracted contours, e) detected blobs, and f) final image with the bounding boxes and their respective reference frames.

After all these steps, the adopted grasping strategy was based on the number of detected objects, their size (computed through the bounding boxes), and their pose with respect to center of the image.

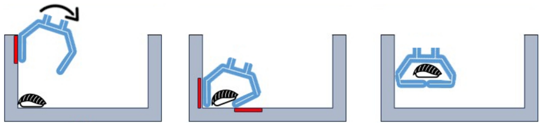
C. Grasp and release strategies implementation

Different grasping strategies have been developed depending on where the food is placed inside a container. The approaches have been determined also considering the part of the container exploited by the scoops. We identified 4 strategies: *i*) unconstrained (i.e., not in contact with the container walls) single quantity of food; *ii*) single food item close to the walls of the container; *iii*) single target food among multiple food items; *iv*) multiple target food items close to each other. Fig. 4 shows a sketch of the strategies.

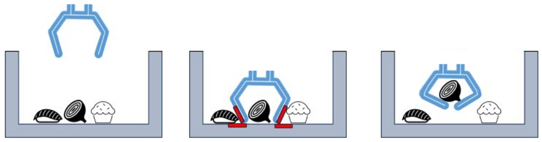
Strategies *i)* and *ii)* aim to demonstrate the effectiveness of the gripper in exploiting the environment around the single item. To differentiate them, we evaluated whether the position of the object with respect to the center of the container was within an empirically predetermined threshold. The threshold was calculated considering the longest side of the container and the maximum opening of the gripper. If the



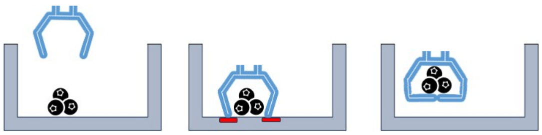
(a) Single and free



(b) Single and wall-constrained



(c) Single between multiple



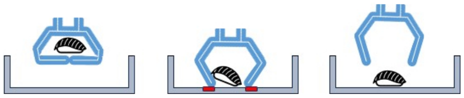
(d) Multiple

Fig. 4: Picking strategies depending on the placement and amount of food items. Grey: container walls, blue: gripper, red: areas where the gripper exploits the environment.

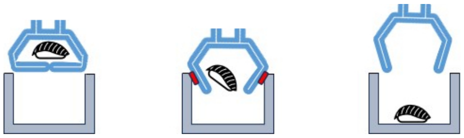
distance between the object and the center of the container is less than the threshold, the gripper performs a top grasp taking advantage of the bottom surface of the environment (e.g., as shown in Fig. 4a); otherwise, the grasp is made, exploiting the container wall closer to the scoops (Fig. 4b).

Strategy *iii*) aims to demonstrate the ability of the DSG to pick a target food when placed among multiple objects by exploiting the scoops to separate them and, at the same time, preventing damage (Fig. 4c). Conversely, strategy *iv)* is executed similarly to strategy *i)*, but it deals with multiple objects simultaneously (Fig. 4d), suitable for tasks where speed is fundamental. In all the strategies, the opening of the scoops is adjusted according to the size of the food item. Besides, when exploiting the walls, the gripper is tilted to place the scoop closer to the lateral surface to adapt to it, as shown in the first sketch of Fig. 4b.

Three placing strategies were implemented, considering containers of different sizes (Fig. 5). The identified strategies highlight the ability of the gripper to adapt to the containers by exploiting their different characteristics. If the release occurs in a large short-walled container, we exploit the environment on the bottom surface of the container to ensure a precise place by the two scoops (Fig. 5a). Otherwise, if the container walls are tight enough not to allow the gripper to move on the bottom surface of the container, the scoops are laid on the container lateral walls to gently release the food item. In this scenario, we considered two potential situations: one where the container is large enough to exploit both the scoops (Fig. 5b) and another one where using both walls is not feasible because the opening of the hand would not be enough to release the food items (Fig. 5c).



(a) Large with short walls



(b) Large enough to let the gripper open partially

(c) Small enough to impede fingers opening

Fig. 5: Placing strategies depending on the size of the target container. Grey: container walls, blue: gripper, red: areas where the gripper exploits the environment.

Fig. 6: Food items adopted in the experimental trials: sausages, meatballs, carrots, cookies, and zucchini.

IV. RESULTS

A. *Experimental setup*

During the experimental phase, the Double-Scoop Gripper was mounted on a UR5 robotic arm (Fig. 1). To test the performance of the DSG, we conducted a pick-and-place procedure, evaluating separately the results of the two tasks. The aim was to demonstrate that the proposed gripper can grasp and release single and multiple objects by applying the strategies described in Sec. III-C. The picking scenario shown in Fig. 1 consists of grabbing food from 3 containers placed at different heights (on a table, between 2 shelves, and above the highest shelf). In the placing scenario, instead, the task was to release the food in containers of different sizes, such as a plate, a bowl, and a glass. For both tasks, we employed 5 real food items of different sizes, shapes, and softness (see Fig. 6). We tested each scenario with all the objects 5 times each, collecting 100 and 150 trials for pick and place, respectively.

To perform the picking, we implemented a Finite State Machine consisting of the following phases: *i*) the robot is moved to a home pose; *ii*) the gripper is placed above a food container; *iii*) the RGB camera performs a scan searching for the food location and, once detected, estimates its size (see Sec. III-B); *iv*) the gripper moves accordingly above the food item(s), regulating also the opening of the scoops; *v*) the gripper starts descending towards the food item and closes the scoops once it reaches the pre-grasp pose; *vi*) the gripper goes up with the grasped object(s). For the placing experiments, assuming a successful grasp of the intended object(s), the steps were: *i)* the gripper moves above the chosen container, *ii)* the scoops open, delivering the food and accomplishing the task.

B. *Success rate for pick and place operations*

The results in terms of success rates for the conducted experiments are shown in Table I, where the denominators of the success rates are evaluated by multiplying the number of trials (25 for each case) by the number of tested food items ($n = 1$ or $n = 3$).

Regarding the picking experiments, we evaluated the four conditions described in Sec. III-C for each object. A grasp was considered successful if the target food was held inside the gripper until it arrived above the releasing container. Table I reports the results of the picking phase (from the second to the sixth column). Overall, the DSG successfully grasped 133 out of 150 objects, obtaining a success rate of about 88.6%. In particular, a single quantity of food placed away from the container walls was picked-up in 24 out of 25 trials, whereas, in constrained cases (i.e., in the proximity of the walls), it was caught in 68% of trials (17 out of 25). Instead, when the target food was placed among others, 22 out of 25 grasps were successful. Lastly, multiple quantity of the same object ($n = 3$) placed away from the walls were grasped in the 94.6% (71 out of 75) of cases.

Regarding the placing experiments, 291/300 (97%) objects were successfully placed, as shown in the last column of Table I. In more detail, the DSG released all the food items in the plate with a success rate of 100% in both single and multiple cases. The same result was obtained when the bowl was the release container (see ninth and tenth column of Table I). On the other hand, releasing foods into the glass was the most challenging. The gripper successfully placed 23 out of 25 (92%) and 68 out of 75 (90.6%) food items into the glass, in single and multiple quantities of objects, respectively.

V. DISCUSSION

Previously presented results indicate that the DSG can successfully grasp and release single and multiple food items of different sizes and shapes. Thanks to the softness of the fingers, it can effectively manipulate irregular, delicate and deformable objects like the ones used in the experimental setup. Besides, the developed strategies fully exploit the gripper features in combination with the environment around the manipulandum (e.g., exploiting the containers surfaces to help the grasp/release). The delocalization of the gripper from the robotic end-effector was demonstrated to be functional for reaching narrow environments (i.e., the container between the two shelves).

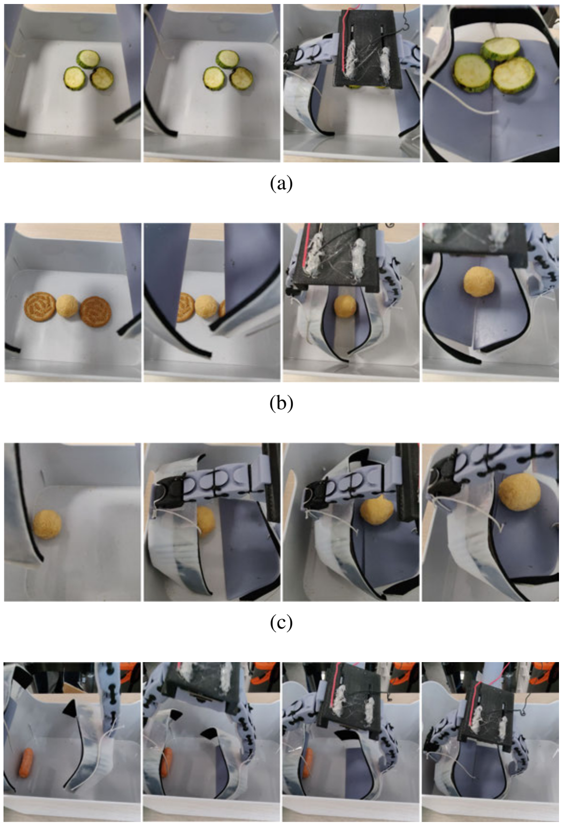
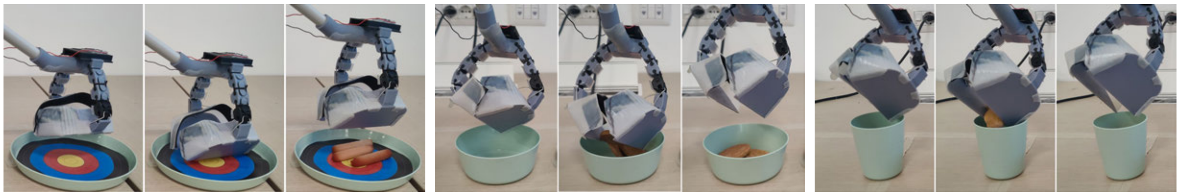

(a)
(b)
(c)
(d)

Fig. 7: Sequences of picks. a) Picking of multiple zuchini; b) target picking of a meatball; c) successful wall-pick of a meatball; d) failed wall-pick of a carrot.

The devised picking strategies work effectively with various objects under different conditions. Exploiting the embedded constraints (i.e., the two scoops), the DSG can delicately handle food items sliding underneath them (Fig. 7a) to pick them up without causing any damage. Almost all objects were easily grasped when placed away from the constraints of the container. The only exception is cookies, which were grabbed 4 times out of 5 (80%) and 13 times out of 15 (86.6%) in the single and multiple cases, respectively. The reason for the failures can be attributed to the stiffness and flat shape of the cookies, which prevented the spatulas from sliding underneath them. On the other hand, grasping becomes quite challenging when the container wall constrains an object. Meatballs are the only items the DSG was able to grab in all the trials (see Fig. 7c), proving the efficacy of the developed strategy and the ability of the gripper to exploit the constraint, coping with narrow environments. Conversely, the failures are mostly due to the fact that the scoop sometimes tends to lose contact with the wall while sliding, causing involuntary deflection (see Fig. 7d). This led to failure, especially with short objects (cookies, zucchini,

TABLE I: Pick-and-place results. Columns 2-6 contain the results from the picking strategies, while columns 7-13 show the results from the placing. n indicates the number of target food items. The overall results of the two experimental phases are represented in bold.

	Pick					**Place**						
Food items	**Free** $n = 1$	**Constrained** $n = 1$	**Target** $n = 1$	**Free** $n = 3$	All (item)	**Plate** $n = 1$	$n = 3$	**Bowl** $n = 1$	$n = 3$	**Glass** $n = 1$	$n = 3$	All (item)
Meatballs	5/5	5/5	5/5	15/15	30/30	5/5	15/15	5/5	15/15	5/5	13/15	58/60
Cookies	4/5	3/5	3/5	13/15	23/30	5/5	15/15	5/5	15/15	5/5	13/15	58/60
Carrots	5/5	4/5	5/5	15/15	28/30	5/5	15/15	5/5	15/15	5/5	15/15	60/60
Sausages	5/5	2/5	5/5	14/15	26/30	5/5	15/15	5/5	15/15	5/5	15/15	60/60
Zucchinis	5/5	3/5	4/5	14/15	26/30	5/5	15/15	5/5	15/15	3/5	12/15	55/60
All (strategy)	24/25	17/25	22/25	71/75	**133/150**	25/25	75/75	25/25	75/75	23/25	68/75	**291/300**



(a) (b) (c)

Fig. 8: Sequence of multiple placement. a) Sausages in the plate; b) cookies in the bowl; c) meatballs in the glass.

and sausages). Note that, currently, the sliding of the scoop is controlled in open loop. Thus, a more accurate control of the scoop descent along the wall (e.g., implementing a force control strategy) could increase the effectiveness of the strategy. Another ability of the DSG is to exploit the scoops to perform precision grasps, as shown in Fig. 7b. In this strategy, the role of visual feedback is crucial in detecting the targeted food item. Once located, the gripper adjusts the closing of the scoops to easily separate and catch the target food among multiple objects.

Overall, the experimental trials validated the developed strategies for placing. As it can be noticed from columns 7-13 of Table I, most of the releases were successful for all the objects. A perfect score was achieved for the sausages and carrots, releasing the objects correctly every time. Indeed, their thin shape was helpful, but even with round items like the meatballs and the cookies, a success rate of 96.6% was obtained. Fig. 8 reports a successful placement in the three containers. The most challenging food item to release was the zucchini, which presented 55 out of 60 successful placements. Moreover, the zucchini was the only item that showed a failure in the single placement. This failure was mainly due to the sticking property of the zucchini surface, which inhibited the sliding on the scoops when tilting the gripper. Unable to slide, these objects tended to stay in the middle of the scoops, falling outside of the glass during the opening of the fingers. This behavior does not happen with the other food items, resulting in successful placements. The glass was the only container where multiple objects failed. The issue in this case was caused by the tightness of the container itself, which hindered the placement of more than two items when their size was notable. Carrots and sausages were easily put into the glass three at a time, whereas with meatballs, cookies, and zucchinis, the gripper lost one of the three picked items during the opening of the fingers.

VI. CONCLUSION

In this work, we proposed the design and application of a novel soft-rigid gripper, the Double-Scoop Gripper. This gripper is specifically tailored to tackle food tray assembly scenarios, where food is placed in restricted spaces. The gripper structure comprises two opposing tendon-driven soft-rigid structures with a rigid component at their tips. To deal with narrow environments, the gripper is situated at the end of a pipe and is equipped with an RGB camera.

Four picking and three placing strategies were developed to fully exploit the gripper characteristics, based on vision inputs. The DSG was tested in pick-and-place trials to validate its design. The experiments showed that the DSG is able to comply with the food fragility without damages, and to reach containers in narrow environments. The gripper achieved a high success rate in both grasp and release tasks, exploiting the environment in different conditions.

In some of the tests (e.g., during sliding along the container wall), we noticed possible limitations of the proposed design, but these can be overcome by modifying the fingers structure to obtain an improved control over the opening motion to better adapt the scoops to the environment. Also cases of sticking of food items to the scoops were observed, and we will study strategies to reduce this phenomenon. Future research will also focus on implementing a prismatic joint to substitute the actual fixed pipe to increase the range of motion of the robotic arm and achieve configurations that previously were unfeasible.

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