Soft hands with embodied constraints: the soft ScoopGripper

Soft Hands with Embodied Constraints: The Soft ScoopGripper

G. Salvietti[1,2], Z. Iqbal[1], M. Malvezzi[1,2], T. Eslami[1] and D. Prattichizzo[1,2]

***Abstract*— The design of robotic grippers requires the accomplishment of several contrasting requirements. Research in under actuated soft hands is a lively topic, with several potentialities and challenges. Soft hands are simple, robust and able of adapting to uncertain environment and operative conditions, however their intrinsic compliance and underactuation reduce control capabilities and precision. Recent studies attempted to compensate this limitation by wisely exploiting environmental constraints and considering them as supports to accomplish the task rather than obstacle to avoid. The development of grasp primitives taking into account environment features leaded to interesting and encouraging results. In this paper, we propose to embed on the hand the positive aspects of studies on environmental constraints exploitation. We present a modular under actuated soft hand in which we added a scoop as a feature of the palm, which simplify object grasping. The scoop allows to grasp objects in narrow spaces, augments the possible contact areas, allows to obtain more robust grasps, with lower forces. The paper illustrates the main design principles, a prototype and experimental results.**

I. INTRODUCTION

This paper proposes a novel design of a robotic hand with two soft fingers and a flat surface (Fig. 1). The concept is much deeper than it appears. The main idea behind is a novel approach to the design of soft hands which includes not only the soft fingers but also the constraints, such as flat surfaces.

In soft manipulation, robotic hands are compliant to adapt to the shape of the object to grasp [1], [2], [3]. Soft hands are largely underactuated and do not usually have enough dexterity to execute a precision grasp. Most of the grasps are of power grasp type [4] and the grasp planner is enriched with the exploitation of the environmental constraints to adjust the object position and then grasp it [5]. The environment, such as a planar surface, represents a constraint able to reduce the uncertainties that can be exploited by the robotic hand [6]. This concept is in contrast with classic grasp planning for rigid hands where the environment is treated as a disturbance to avoid. Such enabling constraints are typically considered as part of the environment and to the best of our knowledge, no one proposed to include a constraint, such a planar surface, into the design of the gripper to grasp object in combination with the soft fingers. Embodying the constraint in the design of the hand is novel and allows to design primitives of soft manipulation that are independent of the environmental constraints, at least to a certain extent, since the constraint is available and does not need to be detected in the environment. The idea is described in Fig. 2. On the left, a robotic hand pushes the sphere on the flat surface to constraint it to the corner and then grasp it. On the right the robotic gripper is designed to embed the constraint in the design of the hand. In this case, the robot hand does not need to exploit the environmental constraints that are already in the design of the hand. Of course, this is one of the many possible primitives that can be designed on a soft hand embodying the constraints.

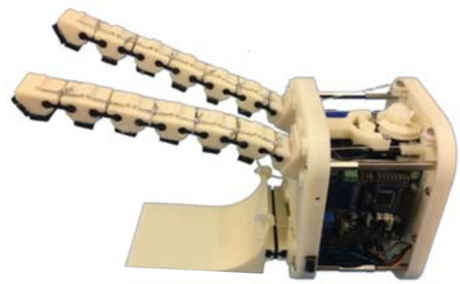

Fig. 1. The Soft ScoopGripper.

Regarding dexterous in-hand manipulation, one might observe that one of the limitation of including constraints such as a planar surface, might reduce the dexterous manipulation of the robotic hand. This is certainly true, but it is not a limitation in soft robotics. Soft hands are mainly designed with the aim of firmly grasping an object more than implementing a dextereous in-hand manipulation [7]. One of the main issue of soft hands as designed up to now is that the enabling environmental constraints not always are reachable or detectable by the grasp planning system making difficult to exploit the primitives of grasping developed for soft hands [8].

In this paper, we propose to include the environment by design in the robotic hand. The constraint is embedded in the robotic hand. The Soft ScoopGripper is composed of two soft modular fingers actuated by a single tendon through a differential system, similarly to the fingers designed for the gripper proposed in [9]. Flexible joints connects rigid links so to build a deformable structure able to adapt to the shape of the grasped object. The scoop, representing the constraint, is connected through a flexible hinge to the hand palm. This allows to easily adapt the scoop orientation to the surface where it slides. The soft hinge also allows to actuate the scoop so to move toward the fingers increasing grasp stability as it will be better explained in Sec. II. The solution proposed

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[1]Università degli Studi di Siena, Dipartimento di Ingegneria dell'Informazione, Via Roma 56, 53100 Siena, Italy. [salviettigio, iqbal, malvezzi, prattichizzo]@diism.unisi.it

[2]Department of Advanced Robotics, Istituto Italiano di Tecnologia, Via Morego 30, 16163 Genoa, Italy.

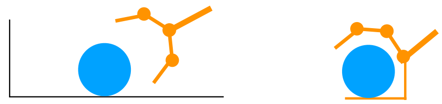


Fig. 2. The main idea of soft hands with embodied constratins.

with the Soft Scoop Gripper may outperform classical soft grippers when dealing with uncertain contacts, complex shape, grasping flat object without exploiting edges or flip motion, soft deformable objects, objects that can be damaged and slippery objects.

II. Design of the ScoopGripper

This section provides details about the design guidelines of the Soft ScoopGripper. The CAD model of the gripper is shown in Fig. 3, whereas the 3D printed prototype is reported in Fig. 1. The device consists of two modular fingers and a scoop connected to the gripper wrist by a flexible hinge. Each module of the fingers consists of a rigid part 3D printed using ASA material (Acrylonitrile Styrene Acrylate, Stratasys, USA) and a flexible part 3D printed in thermoplastic polyurethane (Lulzbot, USA). Polyurethane is used for flexible part considering the high elongation property of this material allowing repeated movement and impact without wear and cracking proving also an excellent vibration reduction. Table I summarises the main technical features and material/geometric parameters of the Scoop-Gripper. The rigid and flexible parts of each module are connected by sliding the thermoplastic polyurethane part in the ASA part. This approach enables an easy assembling process by eliminating the use of any kind of fastener or passive elements to link modules. The rigid parts contain holes to allow the passage of a cable (polyethylene Dyneema fiber, Japan) that provides the tendon driven actuation. The actuation of device is achieved by using two actuators and four tendons running in parallel, each pair of tendon connected to one actuator with two tendons running through the modular fingers and two running through the scoop. The actuators used are two Dynamixel MX-28T (Robotis, South Korea), each having a maximum torque of 3.1 Nm and a maximum angular speed of 684 deg/s. An Arbotix-M controller (Robotis, South Korea) is used to control the actuators of the ScoopGripper. This control solution for Dynamixel motors incorporates an AVR microcontroller, a socket for a XBee wireless radio and the motor driver. Each actuator is linked to a differential mechanism [10] to control the motion of both fingers as the bending of the scoop. The differential mechanism plays an important role in adaptation of fingers' configurations to the specific geometric features of the grasped object. It works in a way that if one of the fingers comes in contact with the object, the other finger can continue its flexion motion. Tendon cables run through the fingers and are attached on one side to the fingertips and on the other to the differential mechanism which in turn is connected with a pulley rigidly attached to the actuator shaft. The actuation of motors result in winding of the tendon cable on the pulley reducing the length of the wire and producing the closure/flexion of connected fingers. The opening/extension of the fingers and the scoop is achieved thanks to elastic force stored in the flexible parts of the modules. The two fingers are connected to the palm of the grippers through a dovetail joint that allows complete rotation of the fingers about their own axis (perpendicular to the wrist). This feature can be exploited to reconfigure finger orientation according to the object to be grasped. Fig. 4 shows possible configurations of the fingers.

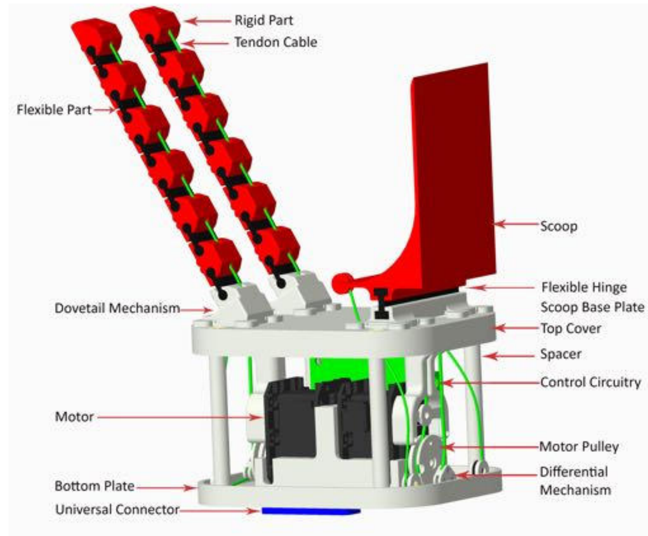


Fig. 3. The Soft Scoop Gripper: An underactuated tendon-driven gripper with two flexible fingers composed of six soft-rigid modules each and a scoop. Modules can be assembled with different stiffness values at flexible joint level, obtained through changing 3D-printer parameters during manufacturing.

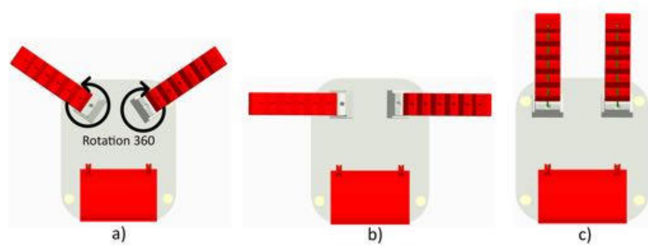


Fig. 4. Possible configurations of fingers achieved acting of the dovetail joint at fingers' bases.

In the rest of the section, we will explain how the scoop and the the finger flexion trajectory can be designed in a soft hand embedding a constraint.

A. Design of the scoop

Hand palm in robotics is an important element since it is the base on which the fingers are connected, but is not often studied from the functional point of view. Typically its main role is to host fingers' actuators and transmission elements and to be the mechanical interface that connects the hand to the wrist of the robotic hand. Nevertheless, hand

TABLE I
TECHNICAL FEATURES OF THE SOFT SCOOPGRIPPER

Technical Features		
Weight (including motors)	500 g	
Max. actuator torque	3.1 Nm @ 12 V	
Max. current	2.8 A @ 12 V	
Continuous operating time	3.5 h @stall torque	
Dimension of the wrist	130 mm x105 mm x 85 mm	
Dimension of a finger	144 mm x20 mm x 15 mm	
Dimension of the scoop	101 mm x70 mm	
Material Parameters	**Flexible Part**	**Stiff Part**
Modulus of elasticity (E)	15.2 MPa	29 MPa
Shore Hardness	85A	80D
Density	1200 kg/m^3	1070 kg/m^3
Geometric Parameters		
width	20 mm	20 mm
length	17.5 mm	23 mm
height	2.5 mm	15 mm

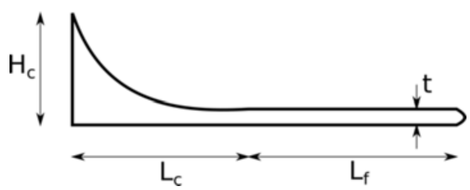
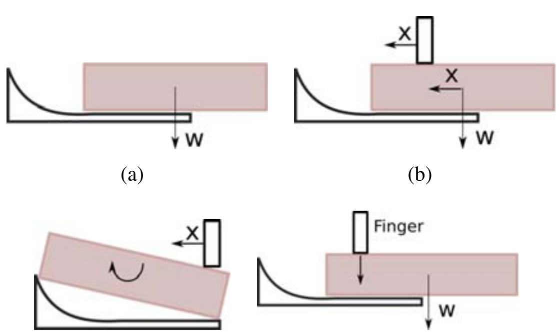


Fig. 5. Lateral view of the scoop and main geometrical parameters.

palm can provide additional contacts with grasped objects, contributing to overall grasp stability. A clever design of a hand palm could improve hand dexterity and manipulation capabilities. The main difference of the proposed hand with respect to the existing ones is that we integrated the palm of the hand with an element, the scoop, that enhance its grasping capabilities.

The scoop is connected to the palm through a joint at his base, so we can reduce its thickness towards the tip to the minimum necessary to realise it and to resist to structural



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

Fig. 6. How the scoop helps the hand to grasp and manipulate an object. (a) The scoop can hold the object when the vertical direction passing through its center of mass is included in the flat surface of the scoop. (b) The fingers can be used to reposition the object on the scoop surface. (c) The curved surface of the scoop can be used to reorient the object in the hand. (d) If object center of mass falls outside the flat surface, the grasp can be maintained if the fingers provide a support, by applying a force on the object.

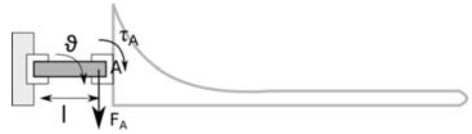


Fig. 7. When a force is applied to the scoop, the flexible joint undergoes to a deformation. F_A, τ_A are the equivalent bending force and torque evaluated at point A, and θ indicates the corresponding rotation.

solicitation. According to the modular approach that we have followed in the design of underactuated compliant hands [11], we can connect the scoop to the palm in three different ways. The first one consists in a fixed connection, that locks the scoop on the palm. This connection is the stiffest and more robust and is suitable when the hand has to lift weight objects, or when a precise positioning is necessary. In the second solution, the scoop is connected to the palm with a compliant joint similar to the one used to build the finger joints. In this case, the scoop has a rotational degree of freedom with respect to the palm, that is not actuated, so its position with respect to the palm is not fixed and depends on the external forces acting on it. This solution reduce stiffness of the scoop, but increases its adaptability to uncertain situations. Finally it is possible to actuate the passive joint connecting the scoop to the palm with a motor and a tendon system, in this way its configuration can be adapted to improve grasp capabilities.

In this paper, we assumed for the scoop a linear extruded profile whose section is sketched in Fig. 5. The thin end allows the scoop to access to narrow spaces, for example the small backlash between adjacent objects packed in a box. The part of the scoop close to the tip is flat, so that it constitute an additional surface providing support and additional contacts to the grasped object. In Fig. 5, we indicated with L_f the length of the flat part. Its definition depends on the dimension and the weight of the objects that have to be grasped.

If the scoop is maintained horizontal, in quasistatic conditions it can hold in equilibrium any object without the use of the other fingers if the vertical direction through the object center of mass is within the scoop profile. In this configuration, hand fingers are not necessary to maintain the grasp (Fig. 6(a)). The hand can move the object without applying supplementary internal grasp forces [12], and this is an advantage when manipulating fragile or highly deformable objects that could be damaged by the application of locally high forces. Furthermore, hand fingers, not necessary to maintain the grasp in this situation, could be potentially used to realise in-hand manipulation of the object in a more safe and robust way (Fig. 6(b)). Scoop thickness increases close to the connection with the palm and its profile becomes curved. In this case the object can be easily and safely rotated within the hand. The maximum rotation that can be obtained depends on object dimension and geometry (Fig. 6(c)). When the object center of mass falls outside the scoop (Fig. 6(d)) the grasp can be still maintained by applying a force with the fingers.

The thickness of the scoop in the flat hand has to be defined so to resist to the external loads and accidental impacts. It is also influenced by the manufacturing technique that we use to produce it. We realised our prototype with ASA material, [1] with $L_f = 60$ mm, $L_c = 38.5$ mm, $H_c = 40$ mm, $t = 2$mm. Printing direction was set perpendicular to the lower flat surface. In this condition the scoop is able to resist a load on its tip up to 100 N.

When the scoop is connected to the palm with an elastic joint, the application of a load on the scoop causes a rotation, that can be evaluated as

$$\theta = \frac{l}{E_j I_j}\left(\tau_A + \frac{F_A l}{2}\right) \tag{1}$$

where F_A and τ_A are the force and torque at the point A of the loads applied on the scoop, E_j is the Young's modulus of flexible joint material, TPU, I is the moment of inertia of joint cross section, and l its length. If the load on the scoop is not centred, the joint will have a torsional deformation. Indicating with $\tau_{t,A}$ the equivalent torsion evaluated in A, the corresponding torsional deformation can be evaluated as

$$\theta_t = \frac{\tau_{t,A} l}{I_t G} \tag{2}$$

where I_t is the polar moment of inertia of joint cross section and G is the shear modulus.

B. Design of the finger flexion motion

The two fingers of the ScoopGripper have been designed so to adapt to the different shapes of grasped objects. Such adaptability is obtained thanks to the flexible joints and to the tendon driven actuation. Flexible joints and the modular structure of the ScoopGripper also allow to design the flexion trajectory of the finger. In fact, differentiating the stiffness of the soft joints, and in particular the stiffness ratio between two consecutive joints it is possible to reproduce a desired fingertip trajectory while closing the fingers. Given a certain desired trajectory, we need a procedure to compute the stiffness values of the joints so that, once the tendon is pulled to close the finger, the fingertip reproduce such course. In the following, we report the main equations of this procedure. More details can be found in [11]. Choosing a suitable movement for finger flexion is important both to ensure that the objects can be correctly grasped together with the scoop and to constrain object motion so to favour the sliding of the scoop under the object itself.

Let us consider the gripper with two fingers and with n_q joints, actuated by a series of n_t tendons. For the sake of simplicity, we model the soft joints as a revolute joints, considering other possible deformations negligible with respect to a rotation axis, so that the variable q_i describing the i-th displacement is a rotation. A complete three dimensional analysis of flexible joint deformation has been recently presented in [13].

[1] Young's modulus, $E = 2.6$ GPa, elongation at break 6%, shear modulus $G = 0.8$ GPa, ultimate tensile strength, $\sigma_{UTS} = 55$ MPa.

We define the vector containing hand joint rotations as $\mathbf{q} = [q_1, \cdot, q_{n_q}]^{\mathrm{T}} \in \Re^{n_q}$, whereas $\mathbf{d} \in \Re^{n_t}$ represents tendon displacements.

The equation

$$\mathbf{d} = \mathbf{M}\mathbf{q}, \tag{3}$$

relates tendon displacements $\mathbf{t}$ to hand joint configuration $\mathbf{q}$. $\mathbf{M} \in \Re^{n_t \times n_q}$ is a transformation matrix independent from hand posture and defined by the size of finger pulleys and by the topology of tendon routing [14].

The hand joint torques $\boldsymbol{\tau} \in \Re^{n_q}$ and the vector containing tendons' pulling forces $\mathbf{f} \in \Re^{n_t}$ can be computed with the dual static relationship

$$\boldsymbol{\tau} = \mathbf{M}^{\mathrm{T}}\mathbf{f}, \tag{4}$$

by applying the principle of virtual work to the gripper. If the fingers are moving without interacting with external surfaces or objects and no external forces are applied on them, the following relationship between gripper status and joints torques can be set

$$\boldsymbol{\tau} + \mathbf{K}_q \Delta\mathbf{q} = \mathbf{0}, \tag{5}$$

where $\mathbf{K}_q \in \Re^{n_q \times n_q}$ is joint stiffness matrix, symmetric and positive definite, and $\Delta\mathbf{q}$ indicates a variation of the configuration w.r.t. a reference rest position of the gripper $\mathbf{q}_0$, i.e., $\Delta\mathbf{q} = \mathbf{q} - \mathbf{q}_0$. We assume $\mathbf{q}_0 = \mathbf{0}$ for the sake of simplicity. If the joints are independent, matrix $\mathbf{K}_q$ is diagonal and Eq. (5) can be rewritten as

$$\boldsymbol{\tau} + \boldsymbol{\Gamma}\mathbf{k}_q = \mathbf{0}, \tag{6}$$

where $\boldsymbol{\Gamma} \in \Re^{n_q \times n_q}$ is defined as $\boldsymbol{\Gamma} = \mathrm{diag}(\mathbf{q})$, while $\mathbf{k}_q \in \Re^{n_q}$ is a vector collecting joint stiffness. The system can be solved taking into account eq. (4) as

$$\mathbf{k}_q = \boldsymbol{\Gamma}_r^{-1}\mathbf{T}^{\mathrm{T}}\mathbf{f}_r. \tag{7}$$

The solution of the system contains the values of the stiffness for the flexible joints that allows to obtain a given configuration $\mathbf{q}_r$ of the gripper when a force $\mathbf{f}_r$ is applied through the tendons. The vector $\mathbf{k}_q$ can be normalized to obtain a base for the subspace of possible stiffness combinations that can be used to track a desired trajectory. The trajectory shape depends on the stiffness ratios between two consequent joints, rather than on their actual value. However, to obtain a complete trajectory, we need to evaluate a sequence of configurations that lead to a sequence of k_q values. We demonstrated in [11] that for several closing trajectories, the values in k_q have little fluctuation in the sequence necessary to complete the flexion motion. This allows to consider an average value for k_q with a reduced error on the trajectory tracking. We then leverage on the possibility of tuning finger joint stiffness values exploiting the potentialities of 3D printing. In fact, it is possible to use, for instance, thermoplastic polyurethane (TPU) as material for realizing the flexible joints. Once a geometry for the joints is defined, it is possible to regulate their stiffness values by selecting the percentage of infill density. This parameter affects primarily material density, but also its mechanical properties. Infill

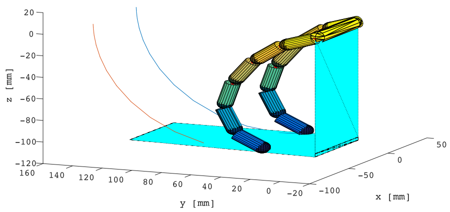


Fig. 8. Simulation to design the flexion trajectory of the gripper's fingers.

density can be regulated during the extrusion process in 3D printers using the stardard technique of Fusion Deposition Modelling (FDM). Mechanical properties for the TPU can be found in [15].

III. Experiments

A. Experimental setup

In this section, we report the experimental results that we obtained with the Soft ScoopGripper prototype. The fingers have six modules which allows a sufficient length to reach the scoop. We have designed using the Syngrasp toolbox [16] a suitable trajectory for the finger flexion, Fig.III-A. The idea was to have a trajectory that could push big objects toward the scoop and push small object toward the palm by sliding on the scoop. The resulting ratio vector $rv \in \Re^5$ between the joints computed as in reported in Sec. II-B is $rv = [0.84\ 0.83\ 1.15\ 2\ 1]$.

To fully exploit the gripper capabilities, we designed an handle and we move the gripper manually to achieve a grasp, see top-left figure in Fig. 10. The handle embeds also the control interface of the gripper that is realised with two push button so to guarantee an easy use. However, the ScoopGripper can also be installed on a robot arm and wireless controlled using the XBee module installed on the gripper control circuit. The handle consist of two parts, a connector plate for the assembly with ScoopGripper and a two button interface to implement the control scheme. It is 3D printed in ASA material. Fig. 9 represents the Finite State Machine (FSM) for control scheme of the device. The handle contains two push buttons, where one button is used to control the flexion and extension of the modular finger and the second one is used to control the bending of the scoop. This finite state machine is duplicated for the fingers and the scoop. A single press of a button activates the event "e1" which initiate the "flexion" of the fingers, as soon as the fingers comes in contact with the object flexion is stopped and the fingers enters a new state "contact/torque control". In this mode, we can regulate the torque/force exerted on the grasped object by continuous pressing the button. Another single activation will again start the "flexion" of the fingers/scoop unless it reaches the state of "fully flexed". The fingers or the scoop can be open/extended by a double activation of the button in any of the states of the finger/scoop. The extension of the finger/scoop can be stopped upon a single activation during extension.

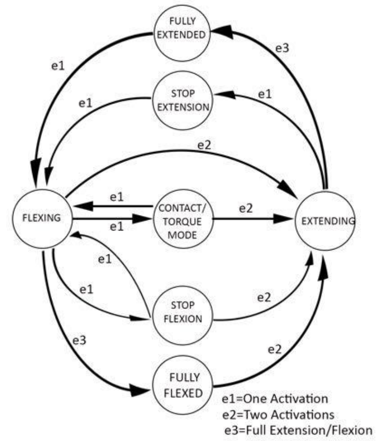


Fig. 9. Finite State Machine for Soft ScoopGripper control

B. Grasping of different objects

We performed a series of grasping with the device assembled as reported in Sec. III-A. The main goal of these experiments is to show the potentialities and versatility of the gripper. In particular, we selected object with different shapes, weight and stiffness. Some of the objects are included in the YCB object set [17]. The obtained grasps are reported in Fig. 10. The weight of the objects ranges from 60 g to 1.6 kg. The approach direction and all the grasping phases have been controlled by the user handling the gripper. For the grasp of smaller objects, i.e. the banana, the lemon and the apple, also the scoop is bent so to increase the grasp robustness. For bigger objects, i.e. the coffee machine, the jug and the box, the scoop is left on its straight position. Note that for the jug and the box the fingers have been rotated so to close parallel to the scoop. This is an important feature of the ScoopGripper that also allows to grasp objects with a cylindrical symmetry without rotating the whole gripper and sliding the scoop under the objects. Two examples are reported in the last row of Fig. 10.

C. Comparison of grip force needed for a grasp

The scoop can also help to improve the robustness of the grasp reducing the force that the finger need to exert on the object. Consider the ball grasped on the top-left side of Fig. 11. The fingers are only used to cage the ball with the help of the scoop and of the gripper palm. In the bottom-left of Fig. 11, the ball is only grasped using the two fingers as it usually happen in classic two-finger grippers. We evaluated the grasp tightness measuring the torque exerted by the servomotor in these two different cases. We performed 10 time the two different grasp asking to the operator to stop closing the finger when it was possible to lift the object. After that, the operator should place the object in a target point 50 cm on the right with respect to the initial grasp position so to test the robustness of the grasp. For the case of the ball grasped with the help of the scoop, the average measured torque for the motor was 0.90 Nm with a standard deviation of 0.21 Nm. When the ball was grasped only by the fingers (basically the gripper was rotated of 180 degrees),

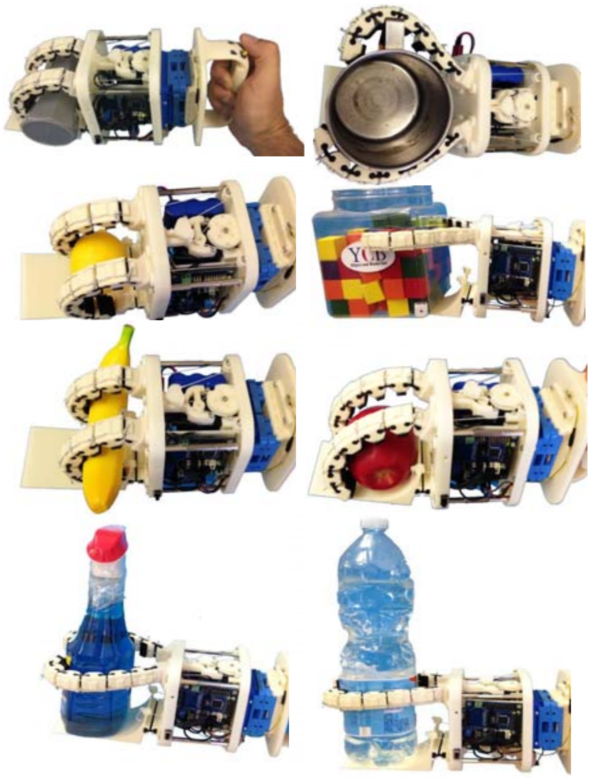


Fig. 10. Different objects grasped with the ScoopGripper. Starting from top left: a toy coffee machine, a jug, a lemon, box with toy cubes, a banana and an apple, a bottle of cleaner and a bottle of water. Note that the object have very different shapes and weights. For the case of the jug, the box of cubes, the water bottle and the glass cleaner bottle the scoop is slid under the bottom and the fingers closed in parallel to the scoop.

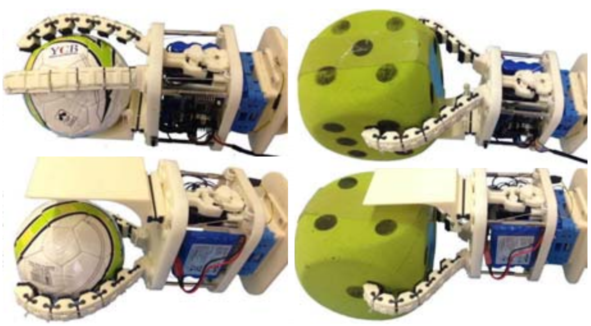


Fig. 11. Grasps exploiting the scoop and grasps only with the fingers.

the average torque measured at the motor was 2.08 Nm with a standard deviation of 0.15 Nm, which is more than double of that required using the scoop. This feature may be very important when handling fragile object such us fruit or vegetable that may be damaged by an excessive force exerted in a reduced area. We repeated the experiment also with a soft dice, see the right side of Fig. 11. In this case, the average exerted torque was 1.05 Nm with a standard deviation of 0.25 Nm, whereas when the dice was grasped only by the fingers the average torque measured at the motor was 2.25 Nm with a standard deviation of 0.27 Nm,

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

Fig. 12. Possible strategy to grasp a book form a pile exploiting the scoop.

D. Strategies to achieve the grasp exploiting the scoop

The aim of this experiment was to show how the Soft Scoop gripper can be used in situation where simple grippers would fail or would require a complex manipulation strategy to achieve a stable grasp. Consider, for instance, the case reported in Fig. 12-a. The goal is to grasp the first book from a pile. We asked to ten subjects to try to grasp the book using the ScoopGripper. All the subjects were able to grasp the book. Fig. 12 represents the most used strategy (7 out of 10 subjects). In Fig. 12-a the scoop is placed between two books. The fingers are then closed so to reach the book, Fig. 12-b. Later, the finger closure is used to help the scoop to slide underneath the book, Fig. 12-c. Finally, the fingers' torque is increased and also the scoop is bent toward the fingers so to increase grasp robustness, Fig. 12-d. Another observed strategy consisted in first pushing the scoop below the book and then activate the fingers. However, this approach resulted a bit slower since the book tended to move forward together with the scoop.

IV. Conclusion

In this paper, we presented a novel soft gripper that embeds a flat surface able to scoop objects. We demonstrate that in several grasping problems, the presence of the scoop allows to reduce the squeezing force required to grasp increasing the grasp robustness. The idea of embedding a scoop may open to the study of a novel generation of soft-rigid gripper that brings the idea of environmental constraints exploitation inside the device. This mainly means that, the capability of soft grippers, and more in general of soft hands, to comply with the environment so to achieve stable grasps using a reduced set of control inputs may be fully exploited also when the constraint is not available. The Soft ScoopGripper itself contains the environmental constrain. Advantages of this solution may be: i) large contact area, ii) compensate uncertainties in contact, iii) lower grip force necessary to maintain the grasp and iv) the possibility to achieve grasp not possible from the top, due to object dimensions or position in the environment.

Currently we are focusing on the design of more advanced scoops that may help in increase grasp robustness. We are also working on exploiting the ScoopGripper as end-effector of a robotic arm for autonomous grasp planning.

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