# A Reconfigurable Gripper for Robotic Autonomous Depalletizing in Supermarket Logistics

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***Abstract*—Automatic depalletizing is becoming a practice widely applied in warehouses to automatize and speed-up logistics. On the other hand, the necessity to adapt the preexisting logistic lines to a custom automatic system can be a limit for the application of robotic solutions into smaller facilities like supermarkets. In this work, we tackle this issue by proposing a flexible and adaptive gripper for robotic depalletizing. The gripper is designed to be assembled on the end-tip of an industrial robotic arm. A novel patent-pending mechanism allows grasping boxes and products from both the upper and the lateral side enabling the depalletizing of boxes with complex shape. Moreover, the gripper is reconfigurable with five actuated degrees of freedom, that are automatically controlled using the embedded sensors to adapt grasping to different shapes and weights.**

***Index Terms*—Logistics, Grippers and Other End-Effectors, Mechanism Design.**

Fig. 1. Rendering of the gripper prototype attached to an industrial robot.

## I. Introduction

A warehouse management system is a fundamental part of the supply chain. Repeated palletizing and depalletizing may jeopardize efficiency in the overall process. Depalletizing can be stressing for human workers since they have to remove manually a large number of weighty boxes, usually one by one.

The depalletization task can be easily accomplished using robots, to speed up the process and increase the logistics efficiency, in all the cases in which boxes to be manipulated are of the same type or standardized. In this scenario, different custom grippers have been developed. For example, in [1], a robotic manipulator performing autonomous grasping, transporting and palletizing is presented. This system ensures more flexibility but only a specific type of objects is considered. In [2], [3] the authors proposed an innovative suction system applied on an autonomous robot able to pick standard boxes from the upper side and to place them on a conveyance line. In [4] a flexible robotic palletizer, mainly designed for structured industrial environments, is proposed. Moreover, in [5] a system comprising an industrial robot and time-of-flight laser sensors is used to perform the depalletizing task. Also, in this case, the target objects are solid boxes of known identical dimensions. The above robotic systems cannot be adopted in small realities like supermarkets where the products are not standardized and the environment is unstructured [6]. This is mainly true in all the cases in which the pallets are heterogeneous and composed of boxes with complex shape. Some cases often used for small products in supermarkets are not always rigid and straight boxes, but can present special features that make them very difficult to grasp using standard depalletizing grippers. Some examples are: (1) boxes with holes for the handles, (2) boxes with easy opening made by making hole patterns in the carton, (3) boxes with no parallelepiped shape such as bottle boxes. In this work, we propose a novel depalletizing gripper, used in combination with a robotic manipulator (see Fig 1), able to grasp the boxes not only from the upper side but also from the lateral side. We found experimentally that this solution efficiently allows bluepicking also all the boxes with a different shape such as those previously described.

The depalletizing gripper designed by the authors is composed of two extendable forks that can slide along a rail, coupled with two suction systems endowed with suction cups. In our design, the box is firstly grabbed from the side using the suction systems; subsequently, it is lifted from one side to leave enough space between the box and what's underneath to allow the insertion of the forks under the box itself; finally, the suction cups are switched off leaving the box firmly resting on the forks. This new grasping paradigm allows our gripper to grasp heterogeneous boxes and products: at the end of the grasping procedure, the box is firmly placed on the forks, allowing a stable position during the robot motions. Moreover, our gripper is sensorized and re-configurable with five actuated DoFs (Degrees of Freedom) to adapt autonomously the gripper to various box sizes.

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To the best of our knowledge, this is the first depalletizing gripper using the described mechanism to grasp boxes from a lateral side.

## II. Gripper technology and operating principle

In this section, the working principle of the proposed depalletizing gripper is described. To obtain a design adaptable to different scenarios, the gripper was developed by considering the following requirements:

1) ability to grasp boxes from top and side;
2) ability to grasp boxes placed over other boxes;
3) ability to grasp boxes with dimensions in the range $[15 \quad 50]$ cm;
4) ability to grasp boxes with weight in the range $[0 \quad 10]$ Kg;
5) automatic detection of the boxes orientation using the embedded sensors;
6) embedded detection of the box weight;
7) automatic reconfiguration.

The novel gripper is bluecomposed by two symmetric modules, each one equipped with a suction system and a fork, that can be reconfigured along the horizontal axis to adapt the gripper to boxes with different dimensions. This design was chosen for the following reasons: (a) the use of two different, independent and re-configurable modules allows the gripper to grasp boxes of different dimensions, involving a single module for small boxes and both modules for larger ones; (b) the use of forks enables the possibility to grasp the boxes from the bottom side by loading the box's weight on the forks itself during handling and not on the suction system; (c) boxes with complex shapes (e.g. bottle packages) or fragile structures (e.g. boxes with easy openings) can be grasped from the side.

The components of the proposed gripper are described in the next sections.

### A. Mechanical structure

The gripper is designed to be assembled on the terminal flange of an industrial robot. This solution allows maximizing the system flexibility and increasing the system workspace, by ensuring the compactness compared to ad-hoc solutions and easy integration in preexisting logistic systems.

The gripper is lightweight with a structure able to handle boxes with a maximum weight of about 15 Kg. Therefore, we choose to use primarily aluminium alloys for the gripper's main parts and stainless steel only for some thin components such as the forks, as described in the next sections.

The main innovation of the proposed design is the adaptability and flexibility to different scenarios. The three main components of the gripper (see Fig. 2) are described below.

*1) Main structure:* The main structure of the gripper is composed of an aluminium frame with two rails placed in the front. A custom sensorized flange connects the gripper to the robotic arm and includes four load cells to estimate the box weight as described in Sect. II-B2. Two independent gripping modules can move with respect to the main frame, thanks to four ball-guides (for each module) sliding on the two rails. The motion of the two modules (D1 in Fig. 2), symmetrical with respect to the gripper centre, is produced by an SD Bidirectional Ball Screw. The ball screw is actuated by a stepper motor. Each gripping module is composed of at least one suction system and one fork.

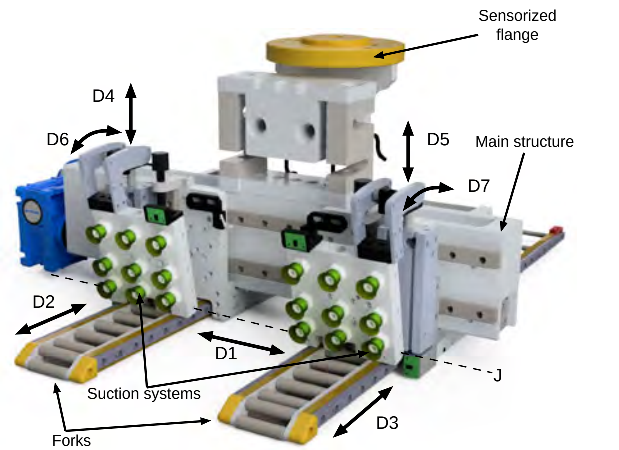
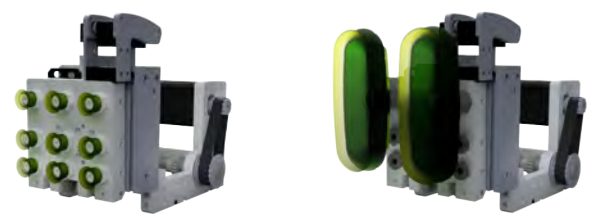



Fig. 2. Gripper degrees of freedom. (D1) enlargment-narrowing, (D2) right fork motion, (D3) left fork motion, (D4) right suction system lifting, (D5) left suction system lifting, (D6) passive rotation of the right suction system, (D7) passive rotation of the left suction system.



(a) (b)

Fig. 3. Suction systems: (a) Matrix configuration of 9 suction cups. (b) Configuration composed by two large suction cups of vertical elongated shape.

*2) Suction systems:* Each suction system is composed of one suction plate placed in the front of the module. On the front side of this plate, several suction cups are disposed. Two different configurations have been tested to evaluate the best solution for each application: (a) a matrix configuration of 9 suction cups shown Fig. 3, which is more suitable for rigid boxes with flat surfaces, (b) a configuration composed by only two large suction cups of vertical elongated shape, shown in Fig. 3. This latter configuration is more suitable for boxes with non-uniform surfaces and requires lower vacuum power because of the increased surface of the suckers. As better explained in Sect. II-A3, one of the phases of the grasping procedure consists in the lifting of the box so that the forks can slide just below it. During this phase, the box is grabbed using the suction system and lifted.

Each suction plate can slide vertically with respect to the module (D4 and D5 in Fig. 2) along a linear guide. This motion is actuated by a pneumatic cylinder to maximise the power-size ratio. Moreover, each suction plate can rotate passively w.r.t. the axis $J$ (Fig. 2). This additional passive DoF has been introduced to reduce the load on the suction cups during lifting. More in detail, considering Fig. 4, the resulting

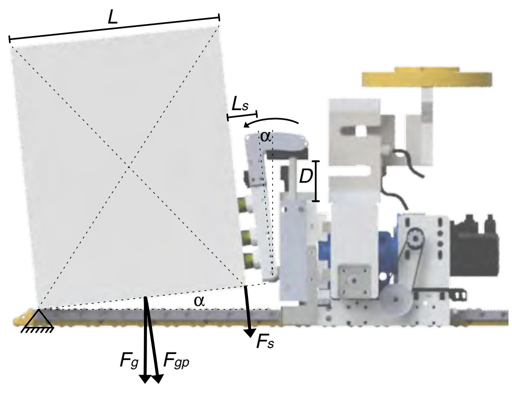



Fig. 4. Force decomposition of the proposed passive mechanism.

tangential force on the suction cups ($F_s$) can be computed from the box weight ($F_g$), by assuming a homogeneous box, using the relation:

$$F_s = F_g \cos(\alpha)/2 \tag{1}$$

where:

$$\alpha = \arcsin D/(L + L_s), \tag{2}$$

$D$ is the pneumatic cylinder displacement, $L$ is the box length in the direction orthogonal to the grasped face and $L_s$ is the distance between the axis of the passive joint $J$ and the suction cups. Notice that the lifting force is approximately halved thanks to the use of the passive joint and no twisting torque is applied on the suction cups, thus substantially increasing the grasping capability. In our design the combination of the actuated vertical motion and the passive motion has been obtained using a custom curved guide (see Fig. 4). The length of the curved guide has been calculated to obtain the required passive rotation for boxes with a minimum length $L_{min} = 10\,\text{cm}$. By considering Eq. (2), and the max pneumatic cylinder displacement ($D_{max} = 5\,\text{cm}$), the required maximum rotation angle of the passive joint is $\alpha_{max} = 18\,\text{deg}$. The passive rotary motion of the suction systems allows the box to be lifted while leaving a lower edge stacked on the surface below.

*3) Forks:* Each gripping module contains one fork that can slide orthogonally to the suction system (D2 and D3 in Fig. 2) along two linear guides for each fork. The motion of the two forks is independent and is actuated by a pair of double rack-geared transmissions linked to two independent stepper motors. The two stainless steel racks represent the bearing structure of the fork. Each fork includes a pattern of aluminum rollers which are suitably alternated to protrude from the upper and lower sides respectively. This configuration allows the forks to be inserted between two stacking boxes, while sliding on the upper and lower surfaces of both the boxes.

### *B. Sensors and actuators*

*1) Actuation system:* The gripper includes three electrical stepper motors (Oriental Motors AZM series) actuating the main gripper DoFs. In detail, the first two actuators are

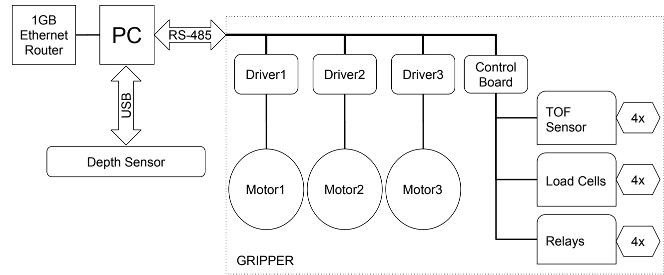



Fig. 5. Functional diagram of the gripper control system.

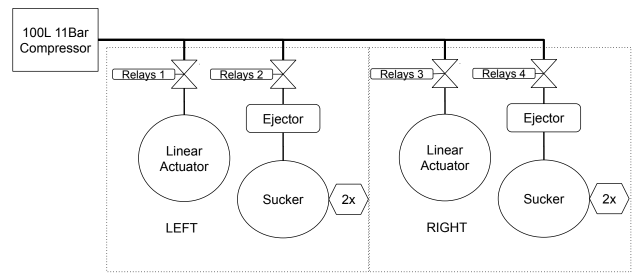



Fig. 6. Functional diagram of the gripper pneumatic circuit.

exploited to move the two forks independently —the extension length of the forks may vary according to the size of the boxes to grab. Then, the third motor actuates the bidirectional screw which moves the two gripping modules to reconfigure the gripper. Each motor is controlled independently by a power electronic board that also acts as a feedback controller. As shown in Fig. 5 each board communicates with the external PC through an industrial-grade network based on an RS-485 Bus in order to have a robust and reliable communication. Each electronic device responds to a unique ID during read-/write operations to control actuators and read the sensors. A microcontroller board, based on an ST Microelectronics $F401$ ARM processor, is in charge of driving four digital electronic valves of the pneumatic system. The pneumatic system on each fork is made of a linear actuator and a vacuum sucker. The pneumatic vacuum suckers (Schmalz SPOB1 100x40 ED-65) are driven by a pneumatic ejector (Schmalz SBP 25 G03 SDA) that gives the right amount of vacuum thanks to the Venturi effect. This combination is best designed to fulfil the task of gripping both rigid cardboard and plastic surfaces up to $15\,\text{kg}$, allowing thus a wide range of boxes. All the pneumatic devices are connected to an external air compressor (11Bar) that powers the circuit. Each pneumatic device can be actuated by the electrovalves connected to the microcontroller board as depicted in Fig. 6.

*2) Load cells:* Thanks to four load cells embedded in the gripper flange, we are able to measure the weight of the boxes in the horizontal configuration as well as the vertical one. The load cells are assembled as shown in Fig. 7, so that the measures can be compared on each couple of sensors. The maximum force applied to each load cell is $500\,\text{N}$ $(50\,\text{kg})$

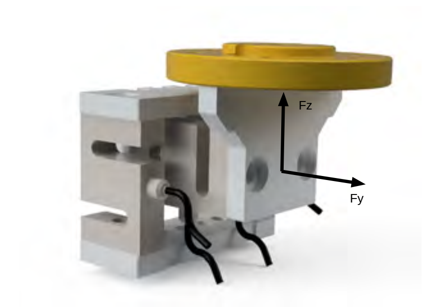



Fig. 7. Load cells configuration. $Fy$ is the force acting to the load cells when the box is picked from the upper side; $Fz$ is the force acting to the load cells when the box is picked from the lateral side.

with a resolution about $10\,\mathrm{g}$. The four load cells are connected to the four Analog to Digital Converters (ADCs) of the microcontroller, which is in charge of the data acquisition and processing. Due to the load cells position, not only is the box weight measured by the sensors but also the gripper weight applies a force due to its gravity dependent on the gripper orientation. Hence, we extract only the gravity components due to the box mass using the force observer presented in [7]. The gripper dynamic model required to apply this method has been identified using the approach presented in [8].

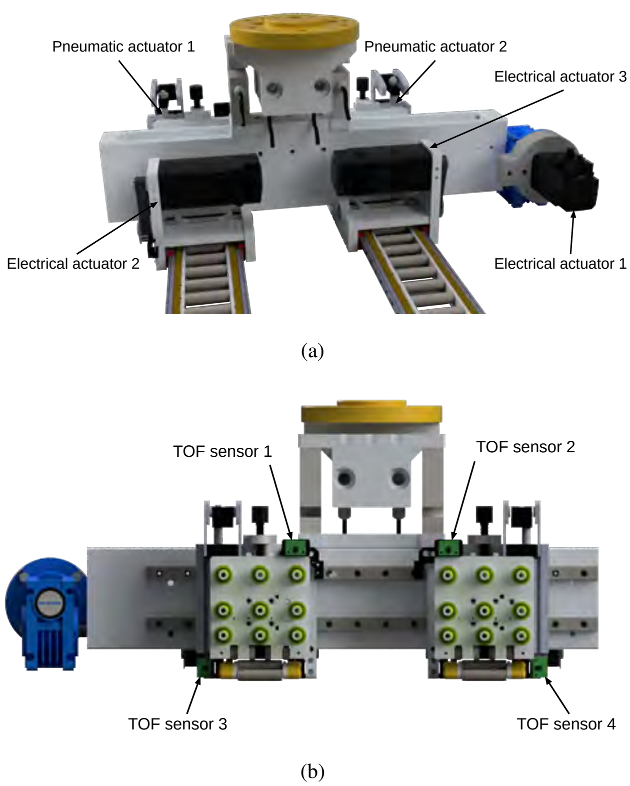



Fig. 8. (a) Gripper actuators arrangement. (b) ToF distance sensors arrangement.

*3) TOF distance sensors:* In our design, four ToF (Time of Flight) sensors are used to measure the distance between the gripper and the boxes just before the approach to get the best trajectory plan. As shown in Fig. 8(b), the four sensors are placed in the frontal part of the system in order to spot the configuration of the front facing flat surface of a box. In particular we identify the four sensors as: $lu$ (Left Up), $ru$ (Right Up), $ld$ (Left Down), $rd$ (Right Down). Notice that the relative distance of the sensors is not always fixed. In particular, while the two sensors of a single suction system are placed in a fixed position, the distance between the left-end and righ-end sensors changes according to the reconfiguration of the gripper. It can be obtained from the relative position of the two sucking systems.

The distance $D$ of the gripper with respect to the box is estimated by the average of the four sensors readings:

$$D = \frac{1}{4}\left(D_{lu} + D_{ru} + D_{ld} + D_{rd}\right) \tag{3}$$

where $D_{lu}$, $D_{ru}$, $D_{ld}$, $D_{rd}$ are the distances of the four sensors respectively.

Moreover, the pitch ($\theta_p$) and yaw ($\theta_y$) angles of the box with respect to the gripper are given by:

$$\theta_p = \frac{1}{2}\tan^{-1}\left(\frac{D_{lu} - D_{ld}}{D_v}\right) + \frac{1}{2}\tan^{-1}\left(\frac{D_{ru} - D_{rd}}{D_v}\right) \tag{4}$$

$$\theta_y = \frac{1}{2}\tan^{-1}\left(\frac{D_{ru} - D_{lu}}{D_{hu}}\right) + \frac{1}{2}\tan^{-1}\left(\frac{D_{rd} - D_{ld}}{D_{hd}}\right) \tag{5}$$

where $D_v$ is the distance between the ToF sensors along the vertical direction, $D_{hu}$ and $D_{hd}$ are respectively the distances along the horizontal direction between the upper and down ToF sensors. As mentioned before, these two distances are changing when the gripper configuration is changed and are obtained online from the horizontal slide motor state.

### C. Grasping procedure

Figure 9 shows the grasping procedure of the gripper according to the following steps: (a) The robot moves the gripper in the neighborhood of the target box; in this situation, we assume that the error of the gripper height, with respect to the base of the box is at most $2\,\mathrm{cm}$. (b) The gripper is reconfigured according with the dimensions of the target box; here, the ToF sensors are deployed to refine the position and orientation of the gripper. (c) The gripper sticks to the box using the suction systems. (d) The suction plates are lifted by the pneumatic cylinders to make room for the forks. (e) The two forks are deployed. (f) The suction plates are lowered to their initial position in order to place the box on the forks. At the end of this process, the box can be safely moved to the desired location.

## III. Experimental validation

The relevant feature of our design is the adaptability to different boxes and the possibility to take non-standard boxes also from the lateral side. We designed a case study to demonstrate the ability of the gripper to grasp boxes with different dimension, shape and weight. The gripper prototype mounted on the terminal flange of an industrial robotic arm KUKA KR60-3 is shown in Fig. 10 We performed a set of 57 experiments considering 19 different boxes picked using

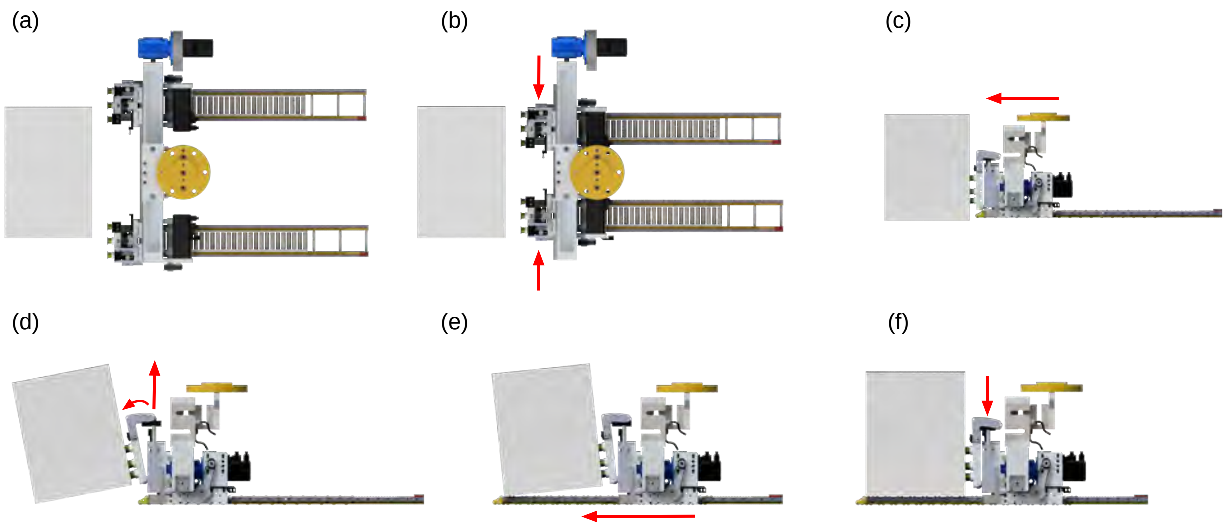



Fig. 9. Actions to grasp a box using the proposed gripper: (a) Gripper approaches to the box. (b) Reconfiguration. (c) Gripper sticks to the box using the suction systems. (d) The suction plates are lifted to give room to the two forks to slide in. (e) Insertion of the two forks under the package. (f) Lowering the suction systems to rest the box on the forks.

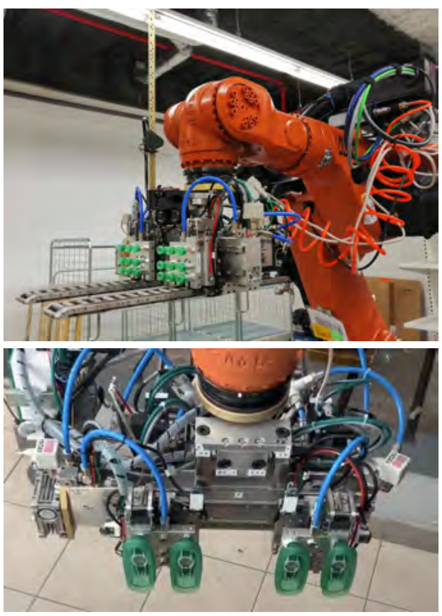


Fig. 10. Real prototype of the gripper assembled on an industrial robotic arm KUKA KR60-3.

TABLE I
GRASPING RESULTS

| Prod. type | Lateral | Frontal | Upper | Note |
|---|---|---|---|---|
| always | no | yes | NA | breaks from above |
| ariel | yes-sf | yes | NA | breaks from above |
| bang | yes | yes | yes | |
| frish-black | no | yes | NA | breaks from above |
| proper | yes | yes | NA | breaks from above |
| viss | yes-sf | yes | NA | breaks from above |
| frosh1 | yes | yes | yes | |
| frosh2 | yes | yes | yes | |
| pampers | yes | yes | yes | |
| spee | no | yes | NA | breaks from above |
| shar | yes | yes | yes | |
| vileda | yes | no | NA | breaks from above |
| ricola | no | no | NA | breaks from above, shape not allow lateral grip |
| das | no | yes | yes | |
| jessa | yes | yes | yes | |
| babylove | NA | yes | NA | breaks from above |
| mozart | no | yes | NA | no upper flat surface |
| small bottles | no | no | NA | no upper flat surface |
| big bottles | no | yes | NA | no upper flat surface |

the proposed gripper. The boxes have been selected, from a typical supermarket pallet, to have a different shapes and dimensions, with weights in a range $[0.5, 10]$ Kg. Each test has been repeated three times. During the experiments, the robot was controlled manually to decouple the performances of our gripper with respect to the robot positioning. The experiments have been carried out by considering the following pattern of actions:

1) Approach the gripper close to the target box.
2) Start the grasping procedure.
3) Move the box in a destination position to verify the stability of the grip.

We tested the grasping of boxes from either lateral, frontal or upper side. Notice that, while the lateral-grasping procedure are performed executing all the actions described in Sect. II-A3, the upper-grasping processes only consists in executing step (c). The snapshots of four experiments (out of the 19 performed) taken from the video attached to the paper are reported in Fig. 11. From left to right, all the steps required to grasp boxes from the lateral side (a–c) and from the upper side (d) are shown.

The experimental results are reported in Table I. The 19 different products are identified with the product name (see Fig. 12 to have a reference image for each product). In our

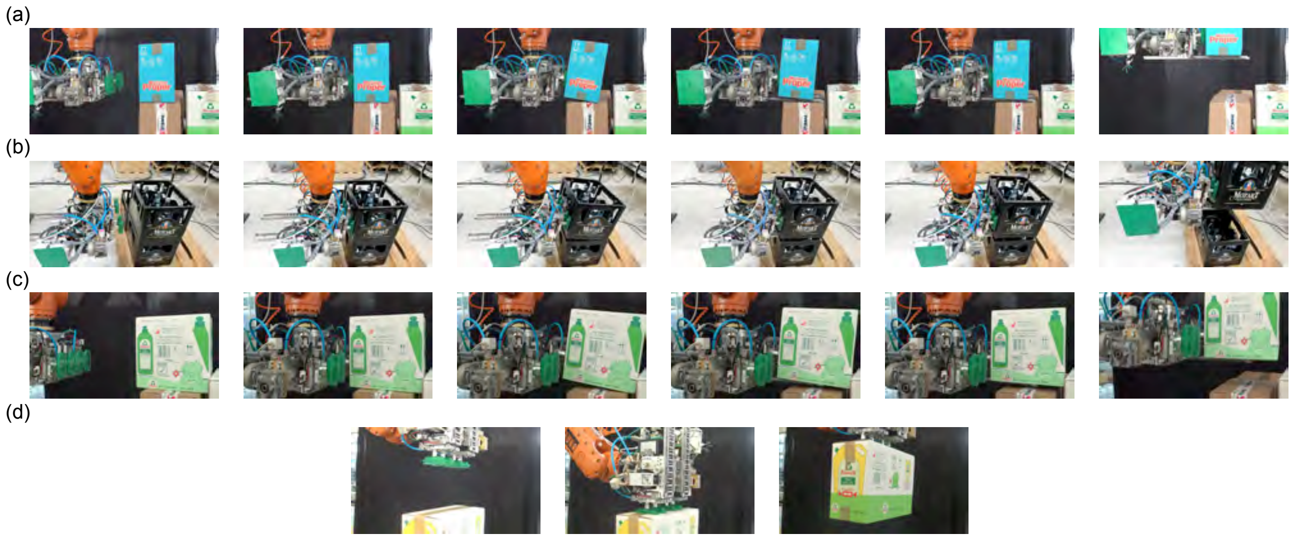



Fig. 11. From left to right, the phases required to grasp boxes from the lateral side (a-c) and from the top (d) are reported: (a) Proper product. (b) Mozart product (box of bottles). (c) Frosh product taken from the small side using only one fork. (d) Frosh product taken from the upper side.


Fig. 12. The 19 different products used in the experimental section.

test, we considered the product as *grasped* (*yes* or *yes-sf* for products grasped with both forks or a single fork respectively) if it was actually taken in more than 2 consecutive tests and *not-grasped* (*no*) otherwise. Finally, NA is associated to boxes that cannot be picked from the specified side. It is possible to see that the proposed gripper was able to grasp products in 17 out of 19 cases. It is worth noticing that, in the considered product set, the 83% of the products are not graspable at least from one side, and the proposed gripper was able to complete the grasping process from another side. This is due to the gripper capability to reconfigure itself and grasp boxes from different sides. In our test, only two products were not correctly grasped. In the "ricola" case, the packaging presents holes and fast opening in all the 6 sides. In the "small-bottles" case, the small size and the curved shapes of the packaging impair suckers to correctly stick on the surface. However, both these cases could be solved by replacing the suction cups with custom ones chosen for the specific application.

## IV. Conclusions and Future Work

In this work, a new concept of a reconfigurable gripper for robotic depalletizing was presented. A new patent-pending mechanism was used to easily reconfigure the gripper to pick boxes of different dimensions and weight both from the upper side and from the lateral side. The effectiveness of the proposed design was evaluated in a real depalletization scenario, by picking 19 different products. The results show a good capability of the gripper to grasp standard boxes, boxes with a fast opening structure and boxes of bottles. Special products such as boxes of small bottles require custom suction systems. In future work, more suction systems will be evaluated to find the best solution in terms of compactness and effectiveness for each type of product.

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