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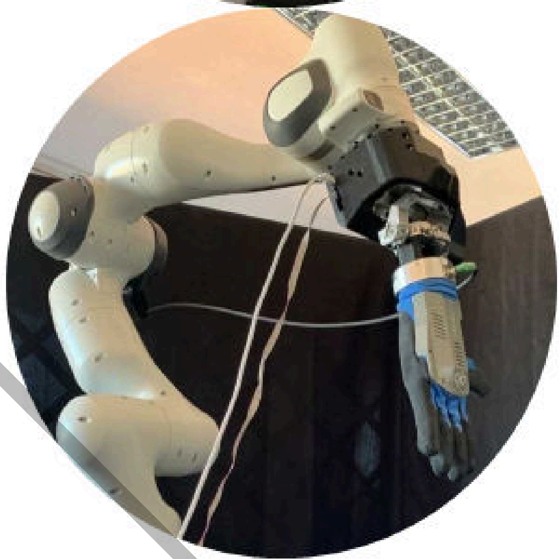

DELIVERABLE 1.2
Preliminary DARKO end-effector

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Figure 1: DARKO lead use case. Parts of varying shapes, weights and packaging are stored in boxes or trays on slanted shelves (see on the right of the picture).

1 Introduction

This report describes the first prototype of the general purpose gripper developed for the DARKO's lead use-case scenario that consists in order picking and commissioning of spare parts (arranged in special boxes on a shelf in a warehouse), inspired by the work flow at Bosch Siemens Hausgeräte (BSH Home Appliances group or BSH), as described in D8.1. In particular, D8.1 describes step by step how the results of DARKO might be demonstrated in an application of the use case of the project, at the ARENA2036 replica. Among the several steps, the general purpose gripper is mainly involved in the following ones:

Picking parts from boxes on the shelf. The robot gets an order (via the user interface on the PC). Each order is a list of objects and quantities. E.g., "collect 5 units of article 111 and 8 units of article 222, and put them all in box B". Objects to be picked are stored in boxes or trays on slanted shelves, as shown on the right in Figure 1. Objects may be well sorted next to each other inside boxes, as shown in Figure 2;

Placing/throwing parts into a (moving) tray. Parts should be placed into trays for further transport on a conveyor belt. The robot may also choose to place the object directly in the target tray, which may be moving, or to throw directly them into a tray for improving efficiency of the robot task.

In light of the above use case scenario, the gripper should grasp objects of different shape, weight, packaging and hence even texture and in narrow space. Moreover, objects may need to be manipulated for reorienting/re-positioning them in the hand for more robust grasping and predictable throwing. The gripper should also close and open quite fast to make possible the picking/placing out from/into moving trays. The gripper should be general enough to also cope with challenging situations, such as picking out objects from boxes that are well-ordered next to each other. Of course, grasping with a multi-finger gripper may be very difficult.

Based on these needs, our idea for a general purpose gripper is a fast in opening/closing, compliant, adaptive hand with manipulation capabilities attached to a robotic arm by a compliant wrist. The hand should be able to use specific hand-tools (without the need of changing substantially the gripper) for coping with challenging manipulation tasks.

(a)

(b)

Figure 2: Objects may be well sorted next to each other inside boxes. This makes difficult the task of picking out with a multi-fingers gripper such as the SoftHand.

As a consequence, the first prototype of the general purpose gripper consists of two main parts: 1) a fast adaptive multi-synergy soft hand (see Section 2) and 2) a two Degree of Freedoms (DoFs) elastic wrist showed in Figure 3(a) (see Section 3). To show the capability of our hand to also use specific hand-tool, we also design a *pneumatic hand-tool* showed in Figure 3(b) (see Section 4), that can be grasped by the above-mentioned general purpose gripper and used to simplify the picking in the above-described challenging situations. The pneumatic tool, which is equipped with a suction cup and a Venturi effect pump, can also be used for throwing objects by apply to the object a thrust force generated by a flow of pressurized air.

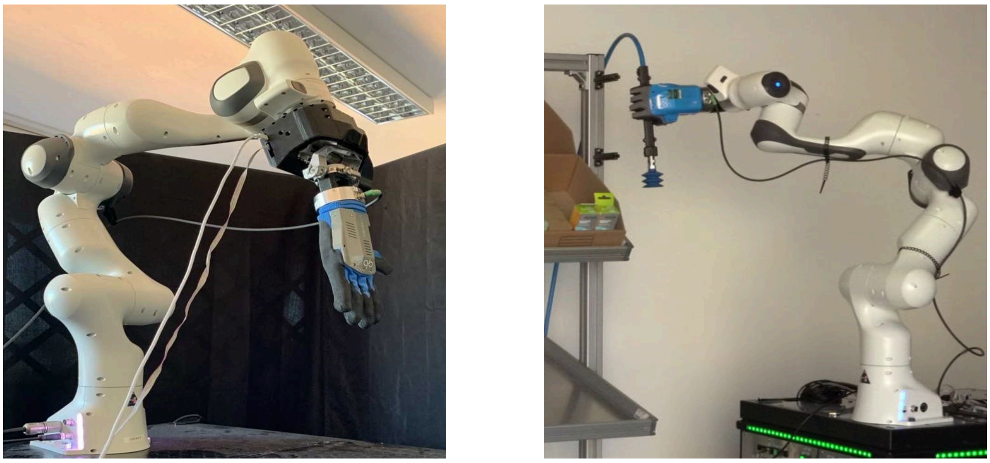
2 Adaptive multi-synergy soft hand

2.1 Fast SoftHand Research

The development of a general purpose gripper to fulfil all the DARKO needs starts from the *qb SoftHand Research* [5] by *qbrobotics srl*[1] which is an anthropomorphic robotic hand based on soft-robotics technology. It is flexible, adaptable and able to interact with the surrounding environment, objects, or even humans while limiting the risk of injuring operators, spoiling products, or damaging the robot itself. Thanks to its soft nature, the SoftHand Research exploits the principles of synergies [11] in an intrinsically intelligent design that is not only safe w.r.t. unexpected human-robot interaction, but also adaptable to grasp different shaped objects without any change in the control action, hence showing an unparalleled level of simplicity and flexibility.

In particular, SoftHand Research has 19 DOFs arranged in four fingers and an opposable

[1] https://qbrobotics.com



(a) **(b)**

Figure 3: (a) The Franka Emika arm equipped with the elastic wrist and SoftHand1 - (b) The SoftHand2 grasping the pneumatic hand-tool.

thumb. To maximize simplicity and usability, however, the hand uses only one actuator. According to our design approach, the motor actuates the adaptive synergy as derived from a human postural database [11]. Actuation of the hand is effected through a single tendon routed through all joints using passive anti-derailment pulleys. The tendon action flexes and adducts fingers and thumb, counteracting the elastic force of ligaments, and implementing adaptive underactuation without the need for differential gears The hand assembly design is shown in Figure 12. Each finger has four phalanges, while the thumb has three. The hand palm is connected to a flange, to be fixed at the forearm, through a compliant wrist allowing for three passively compliant DOFs. The main technical characteristic of the qb SoftHand Research are:

- Flexibility, adaptivity and robustness thanks to the soft-robotics design;
- 19 anthropomorphic DOFs controlled in one single synergy motion;
- Dislocatable and self-reposition phalanges;
- Up to 60 N grasping force;
- Up to 2.0 kg maximum payload;
- Maximum opening/closure time of 1.1 s;
- Total weight of 770 g (including aluminium flange and screws);
- ROS packages and general C++ API available.

Notice that, grasp forces and payloads highly depend on object dimensions and approaching strategy.

To fulfil the requirements of the Darko use case, we upgrade the qb SoftHand Research with a motor able to close and open the hand faster. This feature is useful for quickly realizing the object during the throwing phase, as well as for picking moving objects or placing them in a moving tray. The standard motor of the qb SoftHand Research has a nominal torque of 15 mNm and a reduction ratio of 81 : 1. We change it with another motor that has a nominal torque of 11.1 mNm and a reduction ratio of 62 : 1. As a

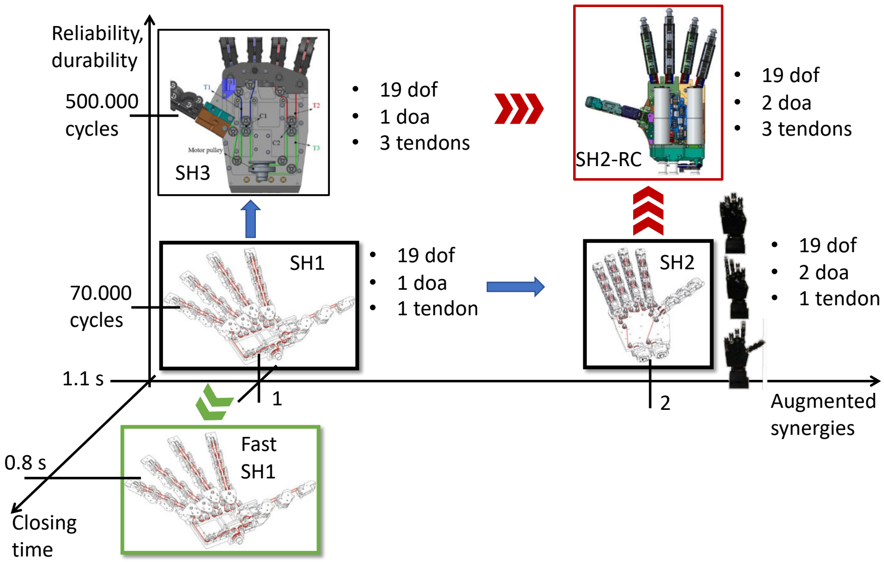


Figure 4: Evolution of the SoftHand toward a long-life device with enhanced skills (in terms of manipulation and closing/opening time).

consequence, the closing/opening time changes from around 1.1 s to around 0.8 s while still ensuring a grasping force able to maintain a stable grasp for the whole Darko object set (around 45 N of grasping force and around 1.5 kg maximum payload).

2.2 SoftHand 2

Apart from reducing the opening and closing time of the SoftHand Research, we also considered the possibility of using a second degree of actuation for augmenting the skills of the SoftHand and hence for increasing the reliability of the hand to embrace big objects and, art the same time, to perform steady and fine grasp for small objects. This will surely bring benefits in picking small objects in boxes and in simplifying the throwing release of them. We hence started from a new SoftHand, called SoftHand-2, that is already developed in our laboratory at UNIPI and now commercialized by qbrobotics srl starting from May 2022. The SoftHand-2 is able to perform the first synergy associated with embracing grasp involving all the joints with uniform distribution of power among all the joints and the second synergy with an asymmetric distribution of the power that allows performing either pinch grasp or index pointing. Our efforts within the Darko project have been mainly directed in improving the durability of the SoftHand-2, an important feature in industrial tasks as the one envisioned in the Darko use-case. The idea to achieve this objective comes from the following observation: distributing the power transmission in the SoftHand from one single tendon that passes through all the joints of the hand, to 3 tendons with simpler routing each, increases significantly the life of the SoftHand (from 70.000 to 500.000 free opening-closing cycles as shown in the first column of Figure 4). We hence adopted the same strategy with the SoftHand-2 rethinking the layout of the hand (the second column in Figure 4) with the aim of extending the duration of its life between failures. The 3 tendons of the new version of the SoftHand-2 are (see Figure 5):

- *Index-Middle finger tendon (green)*: the green tendon extremities are fixed to the fingertips of the index and the middle finger. Moreover, the green tendon passes through all the joints of the fore and middle finger and through Slider 1. Pulling

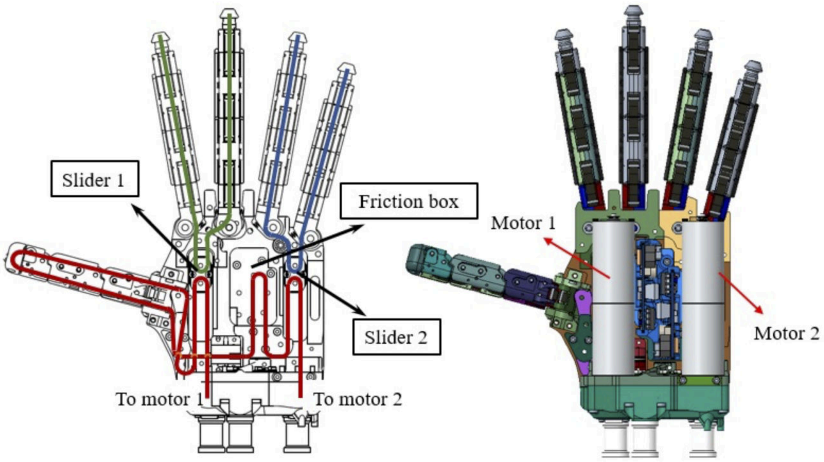


Figure 5: New SoftHand-2 layout. The left picture shows the new tendon routing, while the one on the right shows an inside view of a CAD model of the hand.

down Slider 1 makes possible the index and middle finger closure.

- *Ring-Little finger tendon (blue)*: the green tendon extremities are fixed to the fingertips of the ring and the little finger. Moreover, the green tendon passes through all the joints of the ring and little finger and through Slider 2. Pulling down Slider 2 makes possible the ring and little finger closure.
- *Motor tendon (red)*: one end of the red tendon is attached to motor 1 whereas the other end is attached to motor 2. The central segment of the tendon routes through the thumb and is engaged in both Slider 1 and Slider 2. Wrapping the motor tendon around the motor pulleys make it possible for the thumb to close and recall down Slider 1 and 2 which in turn enable finger closure.

This new layout decreases the chances to break the tendons, while ensuring both under-actuation and adaptability of the hand for both synergies. The activation of the index pointing, or the pinch grasp, needs a certain amount of friction in the motor tendon between the sliders. They are triggered by which motor is actuated. Since the routing of the SoftHand-2 is quite simple, the friction in the tendon between the sliders is not sufficient to enable the second synergies; for this reason, we added a “friction box” between the sliders where the motor tendon wraps around additional pulleys in order to introduce just as much friction as is needed to allow for the second synergies. The friction box allows getting the right amount of friction to enable the second synergy without uselessly dissipating energy. Based on the above-described idea, we built a prototype of the SoftHand-2 with an improved layout and tested it, even if we have not integrated it into the Darko mobile platform and the Franka arm. Figure 6 shows the prototype (in abs) with finger pads on each phalanx made of rubber, to avoid the need of a glove (as for previous SoftHands). The overall size of this prototype is 200 × 148 × 53 mm, which almost corresponds to the average size of the human hand. We are currently testing the durability of the hand with the new layout and carry out the KPIs evaluation as done for the commercial version.

Figure 7 reports a photo-sequence that shows how the hand, thanks to the friction box, is able to adapt and perform different power grasping configurations, which are beneficial for handling and grasping the bigger parts. Moreover, by using the pinch grasp, it is possible to perform a fine pinch grasp to grab the smallest parts (see Figure 8). This

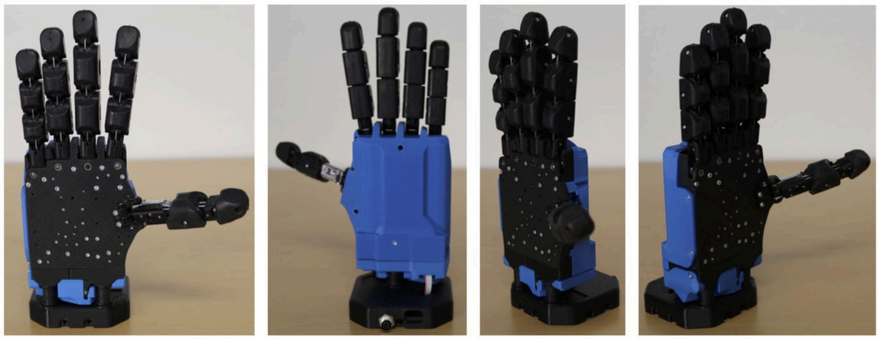


Figure 6: The first release of the SoftHand-2 with the new layout.

(a) **(b)**

Figure 7: Two power grasps of bigger parts from the Darko set of objects.

(a) (b)

Figure 8: A pinch grasp of a smaller part from the Darko set of objects.

feature will bring benefits not only for picking out from boxes, but also to better perform precise placing into boxes and more predictable throws.

3 Elastic wrist

One of the main challenging task to be performed in the use case of the project is picking objects and manipulating them in narrow spaces, such as boxes on the shelf. By observing human arm dexterity and grasp strategies, the main role in providing both a large workspace and a minimal clearance is the human wrist. One year before writing down the DARKO proposal, UNIPI developed a novel soft articulated parallel wrist device that can be easily interfaced with industrial off-the-shelf manipulators to enhance their manipulation capabilities in constrained environments [9]. The idea of developing a new wrist for a manipulator comes from a comparison among the kinematic envelope of robotic manipulators' wrist to their human counterpart through the introduction of the reversed workspace, defined as the volume required by a kinematic chain for a set of end-effector orientations. Results suggest combining the properties of serial and parallel architectures, to obtain a suitable tradeoff between compactness and workspace. The idea in Darko is to start from this first prototype with 2 DoFs in order to deeply understand its benefits and drawbacks in picking up objects from a box on a shelf (highly constrained environment), which is something that we never have done in the past, and then how to extend its capabilities for improving performance of throwing objects with the Panda arm by exploiting its intrinsic elasticity. This information will be then used to develop a new and final version of the UNIPI elastic wrist.

3.1 Concept

The mechanical device developed in [9] was designed specifically for solving the grasp in a box problem, which also corresponds to the main and most complex manipulation problem in the Darko use case. The problem identifies three main design requirements:

- **High dexterity:** increasing the possibility of re-orienting the end-effector by using a spherical wrist.
- **Compact structure:** reducing the reversed workspace by integrating a parallel architecture on a serial manipulator.

- **Adaptiveness:** compliance capabilities to environmental constraints by including in the mechanical concept compliant elements, which also increase system robustness.

The current version of the elastic wrist is a fully integrated 2DOFs add-on module which, combined with the last DOF of the manipulator, provides the complete 3DOFs Hybrid joint kinematics.

The interest in having an elastic element in the wrist is, for the objectives of the Darko project, in the possibility of exploiting it for improving the capabilities of the Franka arm in performing the throwing task. For this reason, in the first part of the project, we directed our efforts in testing the elastic wrist proposed in [9] to understand its benefits and drawbacks in picking out objects inside boxes on a shelf as well as how the mechanical design from both a kinematic and compliance point of views can be improved for another important task of this project, i.e. throwing, that needs a fourth design requirement:

- **lightness and stiffness varying:** other than compact the elastic wrist should also be light in order to be dynamically moved by the Franka arm without causing limits violation and spring value adaptability for a suitable energy storing to be realized at the throwing time depending on throwing specifics (e.g. object weight, distance of throwing etc.).

In the following will be mainly described the current kinematics and series elastic actuation module of the elastic 2 DoFs wrist developed in [9]. For further details, the reader is referred to the paper.

3.2 Kinematics

The 2DOFs spherical mechanism adopted for the compact soft articulated wrist (Figure 9a), is based on the 2DOFs agile eye [1]. It consists of 2 serial chains with a total of 3 passive joints (light grey joints in Figure 9a). The first chain is represented by frames $\{Z_0, Z_1, Z_3, Z_7\}$ in Figure 9a) while the second is represented by $\{Z_0, Z_2, Z_4, Z_5\}$. We define $\dot{q}_p = [\dot{q}_1 \ \dot{q}_2]^T$ as the angular velocities of the active joints, and $\phi_{1,2,3}$ as the Euler angles defining rotations about X_0, Y_0, Z_0 which, based on the literature of artificial wrists [4], correspond to pitch, yaw and roll angles of the end-effector, respectively. Given the active joints orientations q_1, q_2, the solution of the forward kinematics is given by the following set of equations:

$$\tan(q_3) = -\tan(q_2)/\cos(q_1) \tag{1}$$

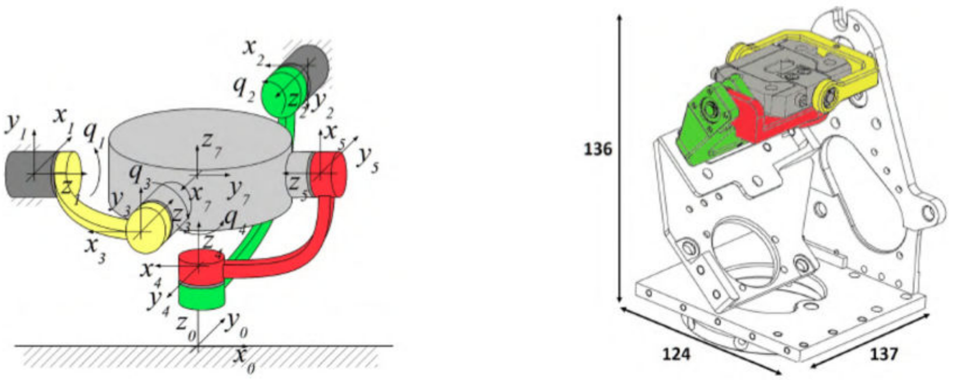
$$\sin(q_4) = \sin(q_1)\sin(q_3) \tag{2}$$

As for the inverse kinematics, given a desired end-effector orientation ϕ_1 and ϕ_2, it is possible to formulate the solutions for the active joints as,

$$q_1 = \phi_1 \text{ or } q_1 = \phi_1 - \pi \tag{3}$$

$$\tan(q_2) = -\tan(q_3)\cos(q_1). \tag{4}$$

where $q_3 \in \{\phi_2, \pi - \phi_2\}$. All possible solutions for previous equations are deeply discussed in [8]. Figure 9b shows the actual implementation of the mechanism kinematics. The yellow fork is the link of chain 1 (i.e. $\{Z_0, Z_1, Z_3, Z_7\}$) while green and red links form chain 2 (i.e. $\{Z_0, Z_2, Z_4, Z_5\}$). The gray part is the mobile platform where the end-effector is connected. The ranges of motion of q_1 and q_2 were iteratively defined. Firstly, the singularity free workspace was determined. Then, the mechanism was designed in order to find the best trade off among wrist size and range of motion. As a matter of fact, the end effector shape/size determines a sub-set of the workspace, free from interferences with the mechanism structure. According to [10] wrist extension has a dominant role



(a) (b)

Figure 9: Courtesy of [9]. Scheme and CAD drawing of the parallel 2 DoFs mechanism. All dimensions are in mm.

over flexion in daily living manipulation activities. Therefore, a reference frame rotation of 40^o was defined to maximize the wrist extension, which is particularly relevant for top grasp in box settings. Concerning the yaw motion, the same study highlights a use of the ulnar/radial deviation of about 15^o. Therefore, this prototype of the compact wrist implements $q_1 = [-80^o, +30^o]$ (flexion/extension), $q_2 = [-20^o, +20^o]$ (ulnar/radial deviation).

3.3 Series Elastic Actuation Module

The two DOFs of the parallel wrist are actuated by a SEA module, which consists of a brushed DC motor (Maxon DCX-22S), (1) in Figure 10, equipped with an integrated planetary gearbox GPX22A (2) with reduction ratio (i) 35 : 1, efficiency (η) 81% and a worm gearbox system A17U10 (3-4) with $i = 10 : 1$, $\eta = 59\%$, for a global ratio of 350 : 1. At this stage, the maximum continuous output torque of the system is 2.36 Nm, the total efficiency of the system is 47.8%. Concerning backdrivability, note that a mechanism self-locks when its retrograde efficiency $\eta\prime = 2-(1/\eta)$ is negative [1]. When there is a series of mechanism, $\eta\prime_{tot}$ is evaluated as $\eta\prime_{tot} = \eta\prime_1 \eta\prime_2 \dots \eta\prime_n$, thus, the SWR is backdrivable. Angular contact bearings (5) were selected for supporting the shaft of the worm. They serve a dual function: increase output shaft position accuracy and relieve the Maxon motor internal bearing from axial and radial loads of the transmission. The actuator has a 12 bit encoder as position sensor, located in (6) while its output is the pulley (7). Figure 11 shows the belt transmission system used to connect the output pulley (7) and the mechanism rotation axis (11).

A non-linear elastic transmission system is realized by coupling the belt tensioner with a linear spring on each side of the belt (8-9-10 Figure 11). This design choice, among others, allowed to use off-the shelf components rather than custom designed springs [13]. The non-linear spring mechanism and parameters are shown in Figure 11(b-c), while its model is defined by

$$\tau = (T_2 - T_1) r_p = K(\delta)\delta \tag{5}$$

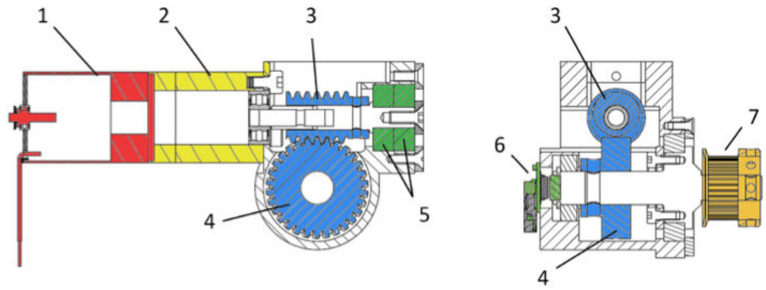


Figure 10: Courtesy of [9]. Actuation module cross sections.

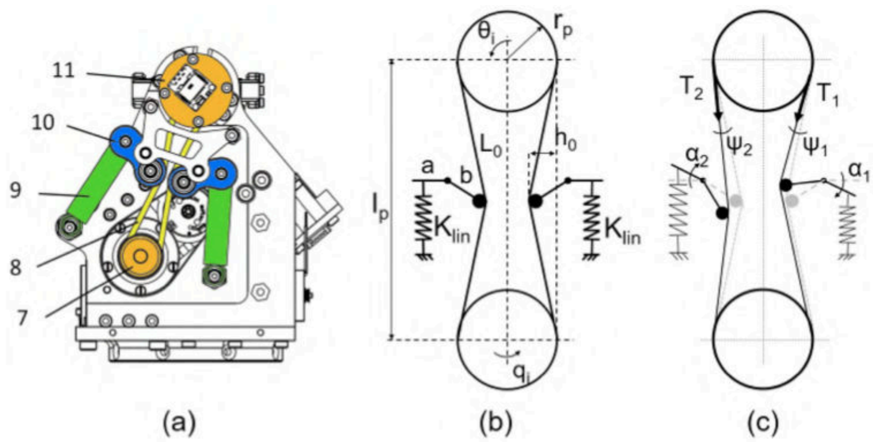


Figure 11: Courtesy of [9]. Non-linear elastic transmission implementation (a) and model, shown in the undeformed (b) and deformed (c) conditions.

	box			shelf		
	can	box	ball	can	bottle	box
human	✓	✓	✓	✓	✓	✓
robot straight E-E	fail	fail	✓	✓	✓	fail
robot angled E-E	fail	fail	✓	✓	✓	✓
SWR	✓	✓	✓	✓	✓	✓

Table 1: Grasp experiment in box setting for different objects in different location inside the box.

where

$$\delta = \theta_i - q_i\,, \tag{6}$$

$$T_i = \frac{K_{lin}\, a\, x_i \cos(\alpha_i)}{2\, b\, \sin(\phi_i)}\,, \tag{7}$$

$$x_i \approx a\, \alpha_i\,, \tag{8}$$

$$\alpha_i \approx \frac{2\, h_0 - I_p \tan(\phi_i)}{2\, b}\,, \tag{9}$$

$$\psi_i \approx \arctan\left(\frac{2\sqrt{(L_0 \pm \delta\, r_p/2)^2 - (I_p/2)^2}}{I_p}\right). \tag{10}$$

The pulleys inter-axis (I_p) and the belt length (L) set the maximum deflection, while the spring stiffness (K_{lin}) is selected to compensate the end-effector weight (0.5 kg) at initial configuration (q_1 , $q_2 = 0$). Provided that the two motors have a different range of motion, the spring maximum deflection has been tuned accordingly. Belt length and pulley interaxis are 201 mm-75.5 mm and 168 mm-59.5 mm, respectively for the two joints. Therefore, the maximum deflection δ_1 is $\pm 10^o$ and δ_2 is $\pm 1^o$. The distributed actuation architecture, let us locate the motors close to the wrist base, improving the compactness of the system. Finally, the Compact Soft Articulated Parallel Wrist sizes are 137 mm × 124 mm × 136 mm, as reported in Figure 9(b). The overall wrist weight is 1.4 kg and consists of 2 SEA actuators (0.35 kg each), a 2 DOFs joint (0.3 kg) and wrist structure including connecting flanges, covers and electronics (0.4 kg). The actuator module weight and size (W×H×D 96 mm×37 mm×44 mm), although in a prototypical implementation, is not far from commercial actuators designs with similar specifications, e.g. the Dynamixel Pro Plus[2] M24P-010-S260-R with weight 0.27 kg, size 42 mm×72 mm×42 mm, continuous torque of 1.7 Nm and gear ratio 257 : 1. As for the 2 DOFs joint, its volume fits within a prism of dimensions 100 mm×80 mm×30 mm which is compact compared with other multi-DOF parallel kinematic schemes, like the High Angle Active Link [12] whose volume fits in a cylinder of dimensions 49 mm×48 mm (D × L) or the quaternion joint [7] with a volume of × mm×90 mm(D×L) and weight 0.45 kg (actuators excluded). The electronic board, software packages and libraries used are part of the Natural Machine Motion Initiative (NMMI) platform[3] [6]. An electronic board is used to control both actuation units. MATLAB/Simulink libraries and a ROS node can be used to control the motors. The different gains of the PI controllers for each motor are tuned based on the Ziegler-Nichols method.

[2] http://www.robotis.us
[3] https://www.naturalmachinemotioninitiative.com/

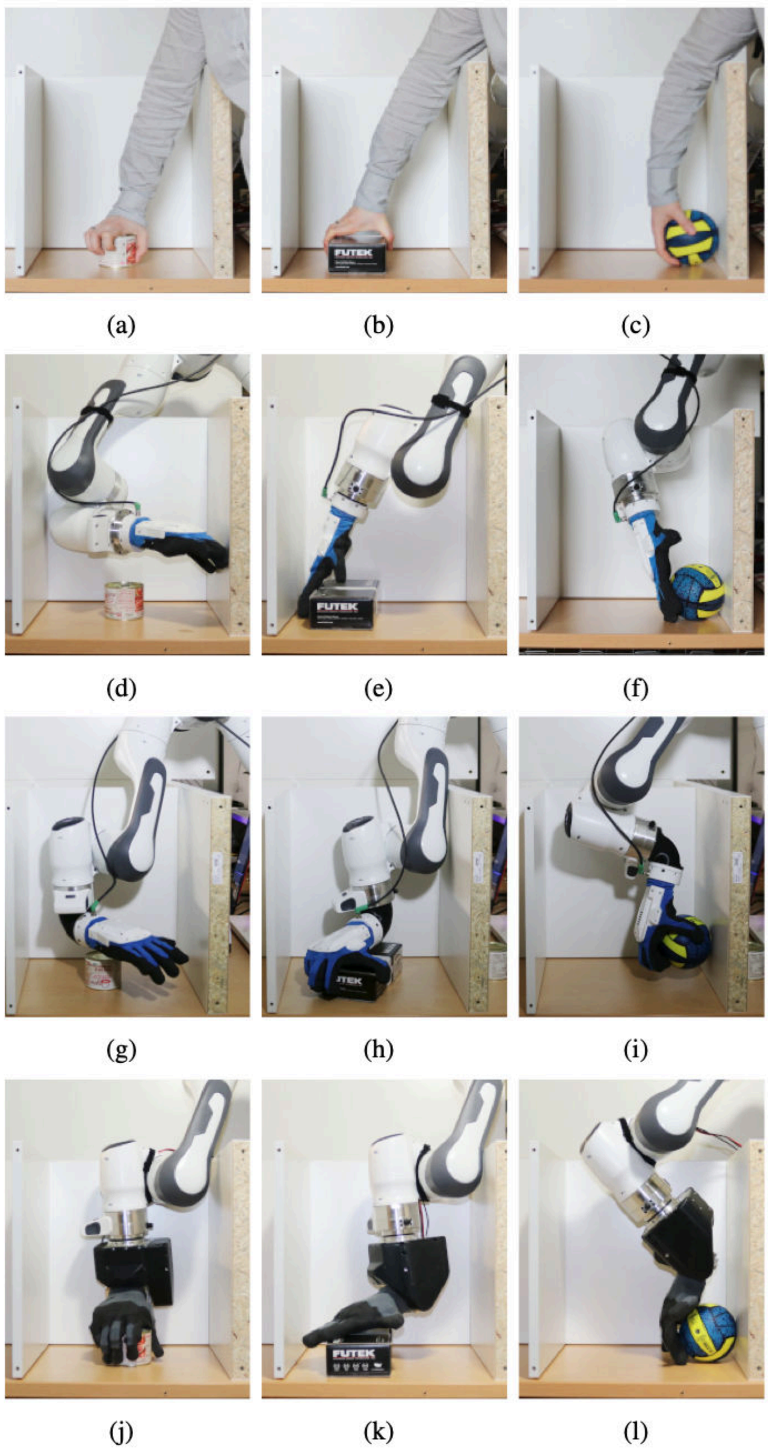


Figure 12: Courtesy of [9]. Grasp experiment in box setting for different objects and manipulator configurations.

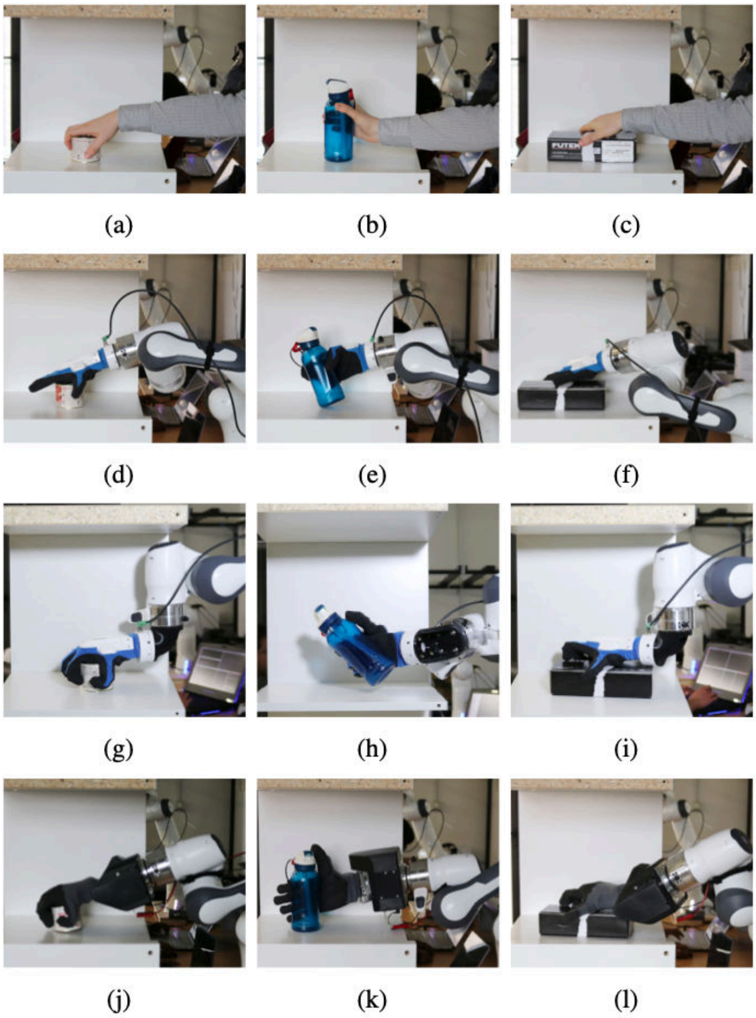
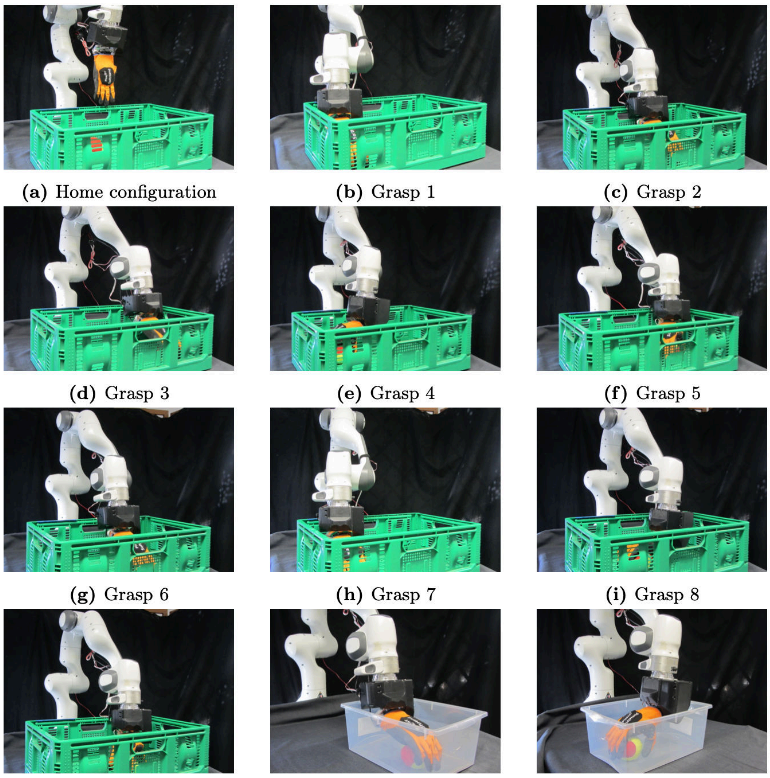


Figure 13: Courtesy of [9]. Grasp experiment in shelf setting for different objects and manipulator configurations.



(a) Home configuration (b) Grasp 1 (c) Grasp 2
(d) Grasp 3 (e) Grasp 4 (f) Grasp 5
(g) Grasp 6 (h) Grasp 7 (i) Grasp 8
(j) Grasp 9 (k) Grasp 10 (l) Grasp 11

Figure 14: Grasp experiment in box setting for different objects in different location inside the box.

3.4 Grasp-in-a-box/shelf experiments

To illustrate the dexterity and compliance of the 2 DoFs elastic wrist within the Darko use case scenario, some experiments have been performed with a physical set-up that consists in a 7DOFs Franka Emika Panda manipulator, the 2 DOFs Compact Soft Articulated Parallel Wrist (SWR) and the Pisa/IIT SoftHand as end-effector.

We also use a set of objects (sphere, cylinder and box) and a shelf with cubic cells, which can be oriented both horizontally (box-like) and vertically (shelf-like). The shelves have cells dimensions 33 cm×33 cm×39 cm (w×h×d). We compared the grasp success rate of the robot in three different configurations: straight end-effector (Figure 12(d)), end-effector connected at 90^o (Figure 12(g)) and end-effector equipped with the SWR (Figure 12(j)). Human grasp is reported as a reference for each grasped object. Figures **??** report the pictures of the test set, and Table 1 summarizes the experimental results for the box and for the shelf, respectively.

Experiments in the box setting: we considered three different grasp types, a top grasp for the low cylinder with a roughly square side section (can), an angled grasp for a large box and sliding grasp for a ball (using the box side as an environmental constraint). Table 1 shows that the robot with both the straight and angled end-effector (E-E), fails to reach a centred object due to wrist collision against the box walls which caused E-E wrong positioning, while the robot with the SWR succeeds (Figure 12(j)). In Figures 12(f-i-l) all the robot configurations succeeded in grasping laterally, and robustly a ball positioned next to the box wall by taking advantage of the wall constraint forces. Other new grasping configurations, more likely to a Darko scenario, are reported in Figure 14 (with a ball as an object). They show the dexterity of the SWR in reaching very constrained locations inside the box, which is one of the feature of the new general purpose gripper should have for accomplishing the Darko manipulation tasks.

Experiments in the shelf setting: in this case we considered a top grasp for a low cylinder, a lateral grasp for a high cylinder (bottle), and an angled grasp for a large box. Table 1 shows the three robot configurations succeeding in grasping a small cylinder from a shelf with a top grasp. In Figures 13(e-h-k), , the robot succeeds in grasping laterally a longer cylindrical object (bottle). The straight E-E robot fails to grasp a box (Figure 13(f)) due to E-E wrong positioning with respect to the object Centre of Gravity, caused by shelf physical constraints. The robot, both in angled E-E and in SWR configurations, succeeds in grasping the box (Figures 13(i-l)). It is worth noticing that despite a similar successful rate among the configurations, the SWR provides, in average, the largest clearance from the shelf walls. Concluding, the robot with SWR configuration has the highest success rate for the box setting, while has the same success rate as the angled E-E in the shelf setting. However, for this end-effector morphology, grasping from a box is much more challenging than the shelf setting, which makes the overall success rate higher for the robot with SWR configuration.

Moreover, these Videos show some picking of a ball inside the box and how the compliance of the SWR becomes useful and allows completing the manipulation task even when, for a planning reason, the end-effector or the grasped object accidentally hits the box or the shelf.

Finally, we also made some tests concerning the throwing task with the elastic wrist. Even if in principle the elasticity should help in increasing the performance of the Franka Emika Panda arm in dynamic tasks, the current elasticity value is too high (hence the wrist too rigid) to be charged of energy taking into account the velocity and acceleration limits of the arm.

4 Pneumatic hand-tool

In the state of the art, there are numerous grippers rigidly mounted on the robot, which allow gripping by means of the use of a suction cup and a vacuum pump. However, they are able to quickly grip and release the object, without being able to deposit the object beyond the working area of the robot itself. There are some other grippers that were born as grippers for picking up objects, and only later, were also tested for throwing objects at short range [3, 2]. In this case, the device, called the "jamming gripper", consists of an elastic membrane, filled with granular material (e.g., coffee powder) which allows, by inverting a pressure, to create a vacuum for gripping and, by means of the introduction of air inside the elastic membrane, to generate a pushing force that allows objects to be thrown. The device has been tested with objects of different shapes and sizes (springs, spheres, cylinders and cubes). However, it has several possible disadvantages which limit its use, especially in the throwing phase. Firstly, the device fails to cover a considerable casting distance (maximum 80 cm). Second, given that the pushing phase is characterized by the introduction of air into the membrane, it is not possible to establish a priori the direction of the thrust which is exerted on the gripped object. In fact, objects of irregular shape, not spherical, influence the contact angle formed between the object and the membrane gripper significantly. Finally, another aspect not to be overlooked concerns the possibility of any damage that could be caused to the elastic diaphragm by gripping sharp or threaded objects, such as in the case of screws or bolts, with the consequent leakage of granular material contained inside the membrane itself.

The pneumatic hand-tool designed by UNIPI is for both picking objects and placing/throwing them in a desired tray. The picking is obtained by a suction cup, which is at the end of the hand tool, and a vacuum pump, connected to the compressor through a dedicated pneumatic line (similarly to the jamming gripper). The placing is simply obtained by deactivating the vacuum pump and eventually by activating the blow off function (already available in the vacuum pump technology by Coval srl) for a fast realizing of the object. By means of a solenoid valve, it is possible to automatically pass from the picking to the pushing pneumatic circuit. The throwing pressure, which defines the pushing force, can be regulated by means of a pressure regulator. Depending on the level of pressure, it is possible to achieve throwing distances beyond the robot's work area. Depending on the maximum pressure provided by the compressor, the distance can be much more than the one it can be achieved by only using the Franka arm capabilities, even with the elastic wrist.

The hand tool is meant to be attacked to the shelf structure to a pair of brackets by means of magnets (see Figure 15) in such a way that the multi-fingers gripper is able to grasp it. The hand tool is mainly conceived and designed to be used by a robotic arm, on a fixed or mobile base, equipped with a multi-fingers gripper, such as for instance the SoftHand research and the SoftHand 2, described in previous sections. Indeed, the hand tool is not rigidly mounted as an end-effector of the manipulator, but instead it is fixed in the environment (to the shelf structure in our case) and can be grasped for its use when the manipulation task requires it. By using the hand tool, the picking phase is greatly simplified and can be done even in such a situation where objects inside the boxes are well-ordered next to each other. This is a classical situation where only one multi-finger gripper is not enough.

4.1 Technical description of the hand-tool

The hand tool is able to carry out a gripping action on an object by means of a suction cup and a pneumatic circuit that generates vacuum by means of a Venturi pump. Moreover, it

Figure 15: The hand tool attached to the shelf structure to a pair of brackets by means of magnets.

is also able to carry out a pushing action on the same object through a second pneumatic circuit that reverses the air flow, to throw the object towards a target tray, and if needed, beyond the robot's working area. The information relating to the position and spatial orientation of the objects to be picked out is conveniently given by T2.2 while the one relating to the position and spatial orientation of the target tray is conveniently given by T2.4. Figure **??** shows the entire pneumatic system: the hand tool, which consists of a handle with a suction cup at its extremity (see Figure 15, and in Figure 16 simply represented by the suction cup), is connected via a compressed air hose to the output of a 3/2 (Normally Closed, i.e. normally connecting the picking circuit to the suction cup) solenoid valve (see Figure 16), which allows switching between the picking to the throwing functionalities. The pneumatic vacuum circuit, consisting of a Venturi pump (shown in Figure 17a), allows picking out from boxes the object by generating a certain degree of vacuum. The throwing force and velocity is regulated by a pressure regulator (shown in Figure 17b). Both circuits are connected via a push-in T-fitting to the output of the air compressor. The pressure regulator, whose input voltage range is between 0 and 10 V, allows linearly adjusting the pressure in a range between 0 and 10 bar, which is the maximum operating pressure for this prototype of the hand-tool.

4.2 On the use of the hand tool for throwing

Depending on the position and orientation of the target tray w.r.t. the Darko mobile platform, the parameters to be tuned in order to launch the object in the final desired tray are: 1) throwing position and orientation of the hand tool, 2) level of pressure at the output of the pressure regulator, 3) time opening of the solenoid valve. In particular, the regulation of the input voltage to the pressure regulator, and therefore the effective pushing pressure, as well as the overture time of the solenoid valve allow varying the effective launch distance and object trajectory towards the established target tray. Of

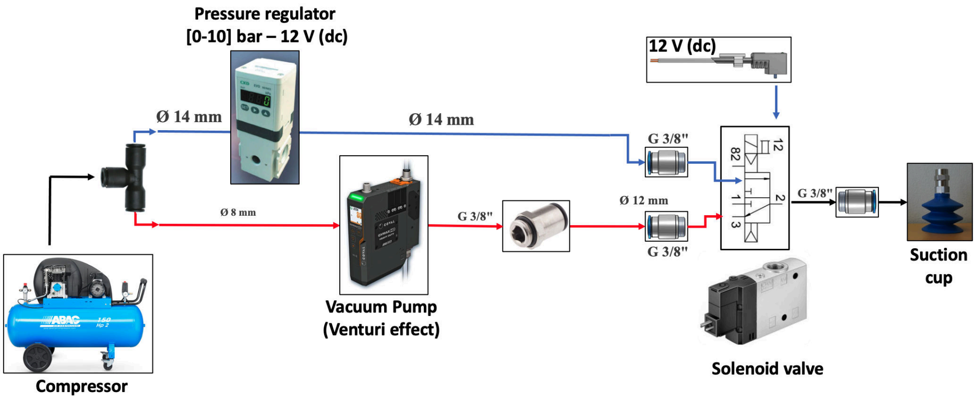


Figure 16: Pneumatic Scheme of the hand tool. The line in blue corresponds to the throwing pneumatic circuit, while the red one corresponds to the picking out pneumatic circuit.

(a) Compact, High Flow Vacuum Pump, LEM+ Series, 85% max. vacuum, 2.5 mm nozzle ID, vacuum controlled 24 V DC NC and controlled blow-off 24V DC NC, electronic vacuum switch, 1 x M12 connector 5 pins, with Powerfull Blow-off.

(b) Pressure regulator series EVD3900-0-10G-AP-B3-3, powered at 24 V DC, maximum pressure 900 kPa, input voltage range between 0 and 10 V, pneumatic port size G3/8, output voltage range between 0 and 5 V, error (PNP), B-type bracket, floor mounted.

Figure 17: Components of the pneumatic circuit for picking out and throwing parts.

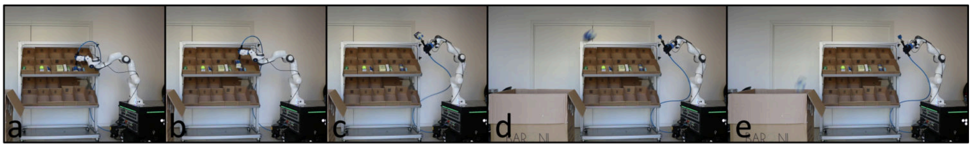


Figure 18: Dishwasher Filter throwing with the pneumatic hand-tool. Pictures (a) and (b) show the vacuuming phase, while pictures (c) - (e) the throwing phase.

course, also all possible dynamic effects, such as air resistance, friction, aerodynamics, irregular shape of objects can influence the object trajectory. However, they also are very difficult to be modelled and accurately predict how all these parameters influence the throwing performance. As a consequence, we used a data driven algorithm over a database of several throwing tests with one parallelepiped object from the Darko set of parts and then tested the resulting algorithm with similar shaped objects.

The tool for picking up and depositing objects was tested during the pre-integration week at the ARENA2036 in Stuttgard with Darko mobile manipulator equipped with an anthropomorphic gripper (the SoftHand 2 in our case). In the experiments carried out, a target identified by a green box was chosen, beyond the maximum working area of the robot (equal to 85.5 cm), towards which to launch objects of different shapes, sizes and masses (e.g.: small boxes, sachets with screws and tennis balls). The results obtained have demonstrated that by setting a certain pressure value, the launch angle that the gripping tool forms with respect to the horizontal plane and the launch height, it is possible to carry out the gripping and launching of objects inside a fixed box positioned at a distance of 200 cm from the base of the manipulating robot. Subsequently, experimental tests were repeated, varying the inlet pressure and the position of the box, to understand and study the maximum distance that the launched object could reach. Figure 18 shows the sequences of the time instants of the launch of the 140 gram dishwasher filter.

5 Conclusions

This report described the first prototype of the general purpose gripper that consists of two main parts: 1) a fast adaptive multi-synergy soft hand and 2) a two Degree of Freedoms (DoFs) elastic wrist. We also designed a *pneumatic hand-tool*, that can be grasped by the above-mentioned general purpose gripper and used to simplify the picking in challenging situations. The pneumatic tool, which is equipped with a suction cup and a Venturi effect pump, can also be used for throwing objects by apply to the object a thrust force generated by a flow of pressurized air. The two Degree of Freedoms (DoFs) elastic wrist was an important tester for better understanding the real needs of the project and developing a lighter and less bulky new elastic wrist with variable elasticity.

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