DARKO

Dynamic Agile Production Robots That Learn and Optimise Knowledge and Operations

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DELIVERABLE 1.4
Final 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 final prototype of the general purpose gripper developed for the DARKO's lead use-case scenario that consists of order picking and commissioning of spare parts (arranged in special boxes on a shelf in a warehouse), inspired by the workflow at Bosch Siemens Hausgeräte (BSH Home Appliances group or BSH), as described in D8.1 (see Figure 1). In particular, the gripper should be designed with the aim of grasping objects of different shapes, weights, packaging, textures and even in narrow spaces. 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 that are well-ordered next to each other inside a box (see Figure 2). In this particular case, a multi-finger gripper may fail, but it could be used to grasp a specifically designed hand-tool.

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.

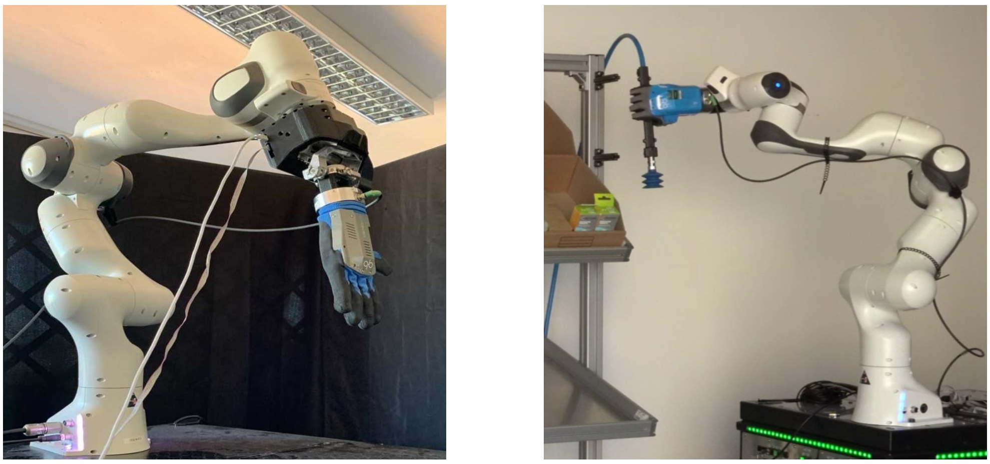
The first prototype of the general purpose gripper developed during the first period consisted of three main parts: 1) a two Degrees of freedom (DoFs) elastic wrist (showed in Figure 3(a)), 2) a fast adaptive multi-synergy soft anthropomorphic gripper, and 3) a pneumatic hand tool that can be grasped by the SoftHand for picking and throwing objects in particular situations. In the following, we briefly recall the results of the previous period referring the interested reader to Deliverable D1.2 for further details.

1.1 Elastic wrist

The elastic wrist used in the first version of the general-purpose gripper, developed in [3], consists of a 2-DoFs spherical joint built using a parallel kinematic structure combined with

(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.



(a) (b)

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

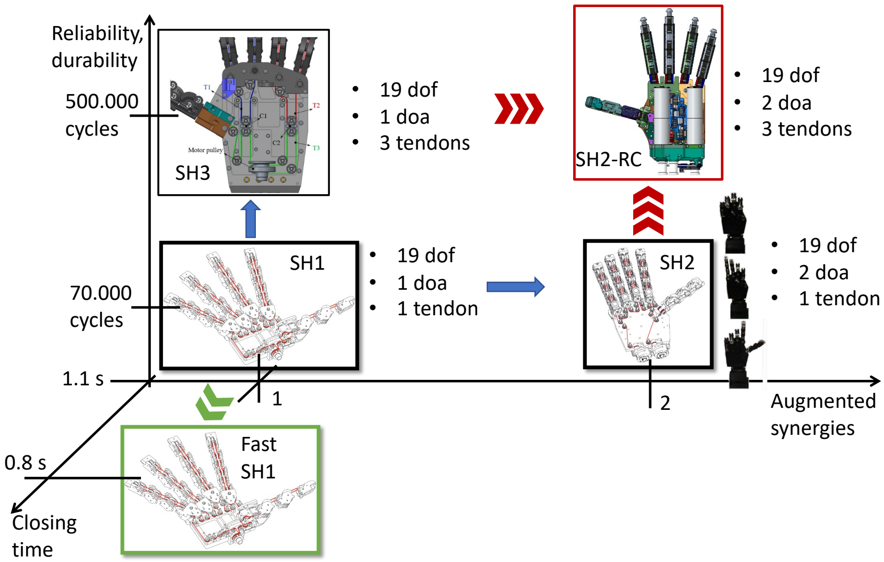


Figure 4: Evolution of the SoftHand toward a long-life device with enhanced skills (in terms of manipulation and closing/opening time).

Series Elastic Actuation (SEA) modules. This design was chosen to fulfill the following 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 architecture composed by the Franka manipulator and the elastic wrist was then tested in the picking-objects-from-boxes use case, showing better performances with respect to the usage of the manipulator only given by the extra DoFs and the intrinsic compliance of the wrist.

1.2 Adaptive multi-synergies soft hand

The work of the previous period regarding the gripper starts from the *qb SoftHand Research* [2] 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.

From this base, two novel versions of anthropomorphic grippers were developed looking forward to the DARKO use case (see also fig. 4 to see the evolution of the SoftHand within the Darko project):

- **Fast SoftHand Research**: This is an upgraded version of the classical SoftHand Research which can open and close fingers faster with respect to the original one.

[1] https://qbrobotics.com

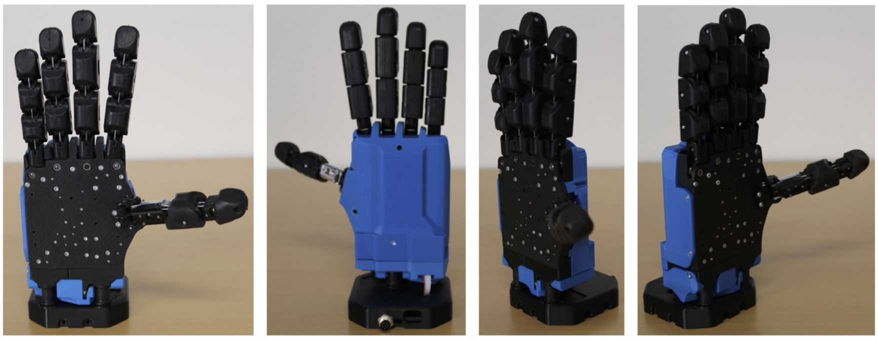


Figure 5: The first release of the SoftHand-2 with the new layout.

This feature is necessary to fulfill some of the tasks of the DARKO scenario (such as throwing or picking up objects in motion) which require a high responsiveness of the gripper.

- **SoftHand 2 with a new layout**: This version of the SoftHand has an additional motor that permits, exploiting a second synergy, to perform also precision grasps of small objects, raising the dexterity of the hand. 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. fig. 5 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).

1.3 Pneumatic Tool

Given the intrinsic difficulties in picking well-ordered objects inside boxes with classic grippers, to overcome this problem we have proposed to add to the system also a pneumatic tool that, if necessary, can be taken by the SoftHand to solve that situation. This solution permits to maintain a certain level of flexibility of the robotic platform instead of a solution that integrates this type of tool directly on the gripper.

The pneumatic tool, which is equipped with a suction cup and a Venturi effect pump, can also be used both for picking objects, generating a vacuum inside the suction cup while it is in contact with the object, or for throwing objects, by applying to the object a thrust force generated by a flow of pressurized air. See fig. 6 for the general scheme of the entire pneumatic scheme described in deliverable D1.2.

1.4 Advancement from D1.2

Starting from the results reported in D1.2, the work of the last period aims to understand the benefits and drawbacks of the previous design of the system for the tasks that the DARKO platform has to be able to perform. We performed further tests by picking up objects from a box on a shelf (i.e. a highly constrained environment), which is something that we never have done in the past. We hence made extensive tests with the aim of extending its capabilities for improving the performance of throwing objects with the Panda arm by exploiting its intrinsic elasticity while maintaining all benefits, that is high dexterity, compact structure, and adaptiveness. The outcomes of this study have been used to define the main characteristics of a new and final version of the elastic wrist (see Section 2) that, with the SoftHand, constitutes the final general purpose gripper that

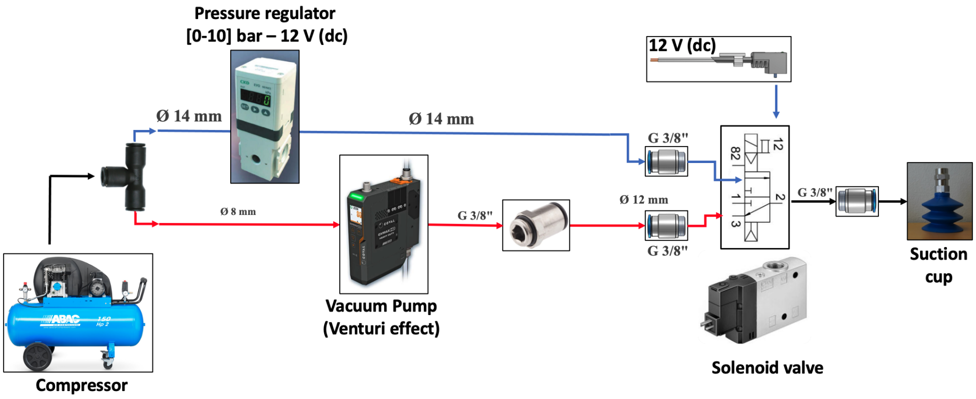


Figure 6: Pneumatic Scheme of the hand tool. The line in blue corresponds to the throwing pneumatic circuit, while the red one corresponds to the picking out pneumatic circuit.

fulfills all requirements for the above-described tasks. Finally, we improved the hand tool pneumatic model and design to increase the reliability of its usage.

2 A new lighter and more compact elastic wrist

Our main efforts have been directed in designing a new elastic wrist whose characteristics are based on the experience we gained during the several manipulation tests we made with the 2 DoFs wrist. The new wrist guarantees the main design requirements needed for solving the grasp-in-a-box problem, while also improving the dynamic capabilities of a rigid manipulator (such as the Franka arm) in very dynamic tasks (such as throwing). Indeed, differently from the old 2 DoFs wrist, which implements one active flexion/extension joint orientation $q_1 = [-80^o, +30^o]$, and a second active ulnar/radial joint deviation $q_2 = [-20^o, +20^o]$, the new one has only one DoF which corresponds to the flexion/extension joint orientation with a wider orientation range of about $[-107^o, +107^o]$. Indeed, for the Darko use case, the additional degree of freedom (ulnar/radial joint deviation) is not that important, it only complicates the mechanics and makes the wrist more cumbersome (which is a negative feature when picking from inside a box). Moreover, to improve the performance of the rigid manipulator in very dynamic tasks (as e.g. throwing objects), it is important to have the possibility of varying the stiffness based on the task (e.g. pick and place or throwing), even during the motion (especially for throwing). Indeed, the old 2 DoFs wrist had only the possibility to set a constant compliance.

As a final remark, it should be pointed out that the elastic wrist described in this deliverable is assumed to be used only with a rigid manipulator, such as the Franka arm, to improve its performance in very dynamic tasks (e.g. throwing). As a consequence, for the elastic arm developed by TUM in T1.3, the final gripper should be the only SoftHand, in all its versions developed for the DARKO use-case, as described in D1.2 (i.e., the Pisa/IIT SoftHand, the fast Pisa/IIT SoftHand and the SoftHand 2 with its evolution toward a long-life device).

2.1 Mechanical description

From a mechanical point of view, the main component of the new elastic wrist consists of a Variable Stiffness Actuator (VSA), and in particular the qbmove Advanced by qbrobotics[2]

[2]https://qbrobotics.com

which is a compact, lightweight actuator with adjustable stiffness. The qbmove Advanced harnesses the inherent mechanical intelligence of its patented variable stiffness system inspired by human muscles (see fig. 7), without the need for sensors on contact surfaces or specialized algorithms for motor current.

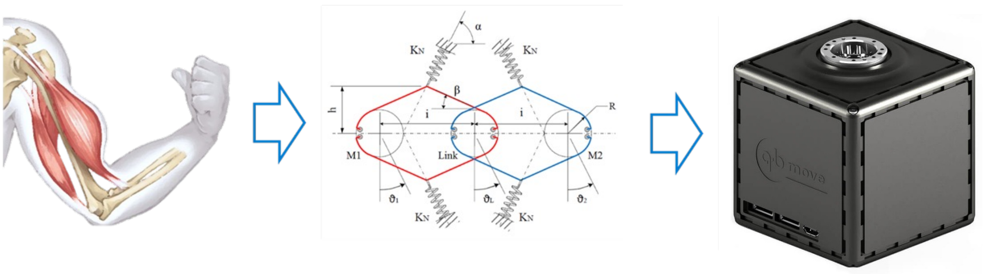


Figure 7: Patented variable stiffness system inspired to human muscles.

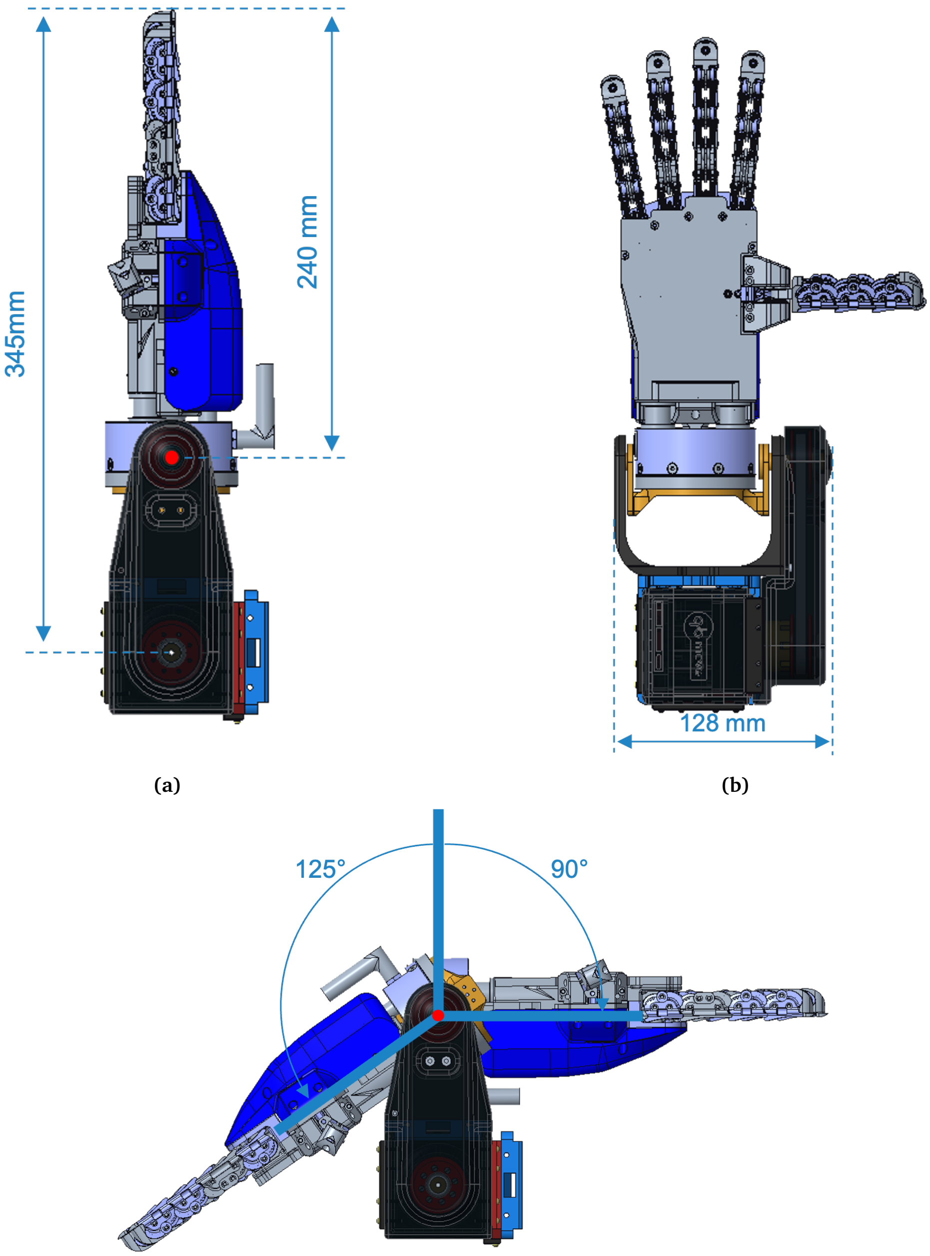
The qbmove Advanced has an USB and RS485 communication interface, a nominal torque 5.5 Nm, a nominal speed 5.5 rad/s, and a nominal Voltage of 24 V. The variable stiffness range is [0.5 83.5] Nm/rad and an active rotation angle of $\pm 180^o$. It is ROS compatible and, as a consequence, it is easy to integrate it within the DARKO platform and it can share with the SoftHand the same communication interface. Its weight is 0.45 Kg with dimensions $66x66x66$ mm.

3 The new general purpose gripper for the Darko project

The new general purpose gripper proposed by UNIPI to fulfill the requirements of the Darko project and the envisioned use cases consists in the SoftHand 2 as an end-effector, attached by a flange to the qbmove Advanced as shown in fig. 8 and in fig. 9. The orientation of the SoftHand 2 (the flexion/extension joint orientation) is obtained with the qbmove Advanced (see Section 2) by means of a transmission mechanism (see fig. 8 and fig. 10) that consists of a toothed belt (in grey) and two pulleys (in red) of equal radius (transmission ratio equal to 1). One of the pulleys is bolted on the output shaft of the qbmove Advanced, while the second is keyed on the shaft on which the SoftHand 2 is mounted by an ISO interface. Of course, by acting on the two motors of the qbmove Advanced, it is possible, not only to change the orientation of the SoftHand, but also to change the stiffness at the end-effector level (even during motion). This is useful for two main reasons: 1) improving the performance of very dynamic tasks, such as pick and place in motion and throwing objects, which are crucial tasks for the purposes of the DARKO project; 2) making the whole robot compliant with obstacles (an important feature when grasping in narrow spaces).

With the objective of further increasing the compactness of the elastic wrist, a new design has been developed as depicted in figs. 11a, 11c and 12.

The idea was to obtain a range of motion for the SoftHand of at least 90^o while at the same time reducing as much as possible the distance between the SoftHand itself and the shaft of the qbmove Advanced, for both the extremal configurations (0^o and 90^o) depicted in fig. 11b. This was obtained by means of a slider-crank mechanism combined with a rack-pinion mechanism, resulting in a 1-DOF variable stiffness overall mechanism capable of having the SoftHand rotate for a 90^o-span in flexion/extension while the centre of such rotation (i.e. the actual wrist of the hand) travels closer to/away from the shaft of the qbmove Advanced. In particular, the qbmove Advanced provides motion to the system through a crank and a rod connected to one of the shafts of a two-shafts carter, which

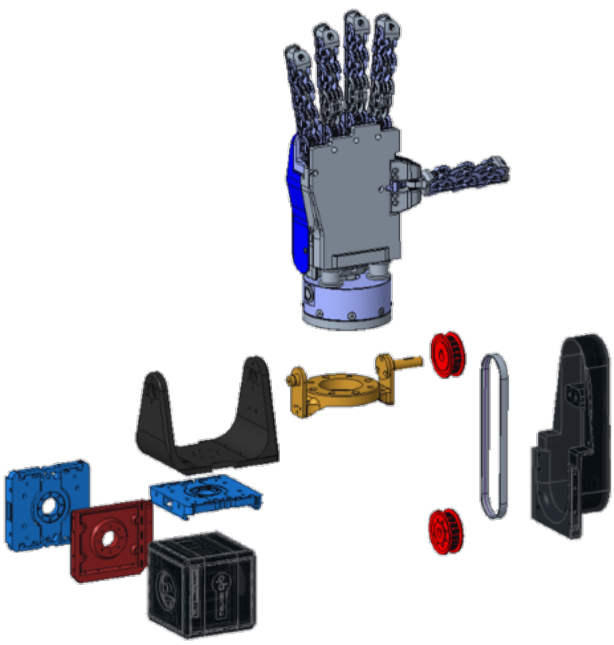


(a) (b)

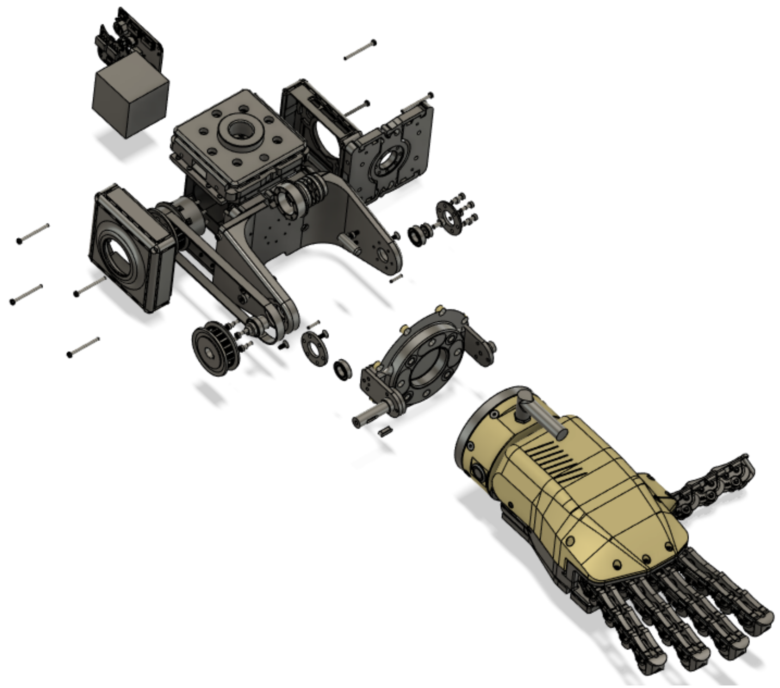
(c)

Figure 8: Layout of the new general purpose gripper that consists of the SoftHand 2 attached to a Variable Stiffness Actuator that acts as an elastic wrist changing both orientation and compliance at the end-effector.

is bolted to the slider and therefore forced to move along the slider rail for an overall stroke of 15 mm. A pinion is free to rotate around the other shaft of the carter, of an angle depending on its linear position with respect to the rack its teeth are in contact with. In this way, the linear position of the carter, dictated by the angular position of the crank connected to the qbmove Advanced, corresponds to a specific linear position of the centre



(a)



(b)

Figure 9: Exploded view of the general purpose gripper that enlighten the mechanical transmission.

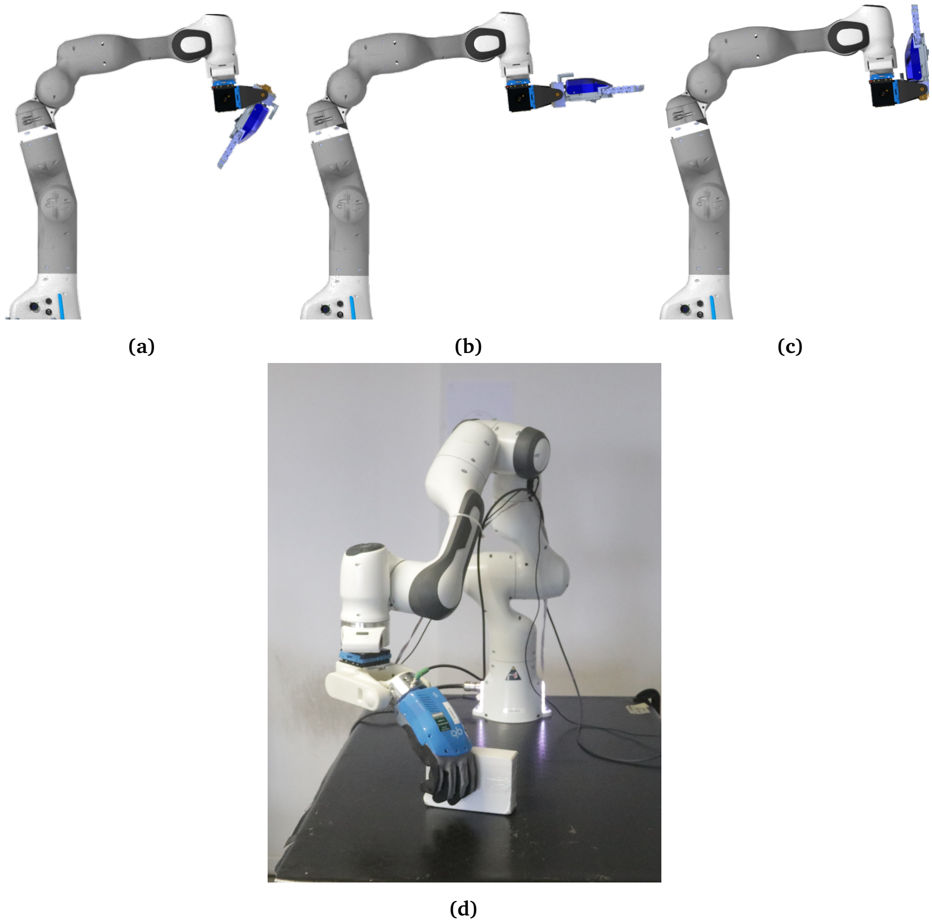


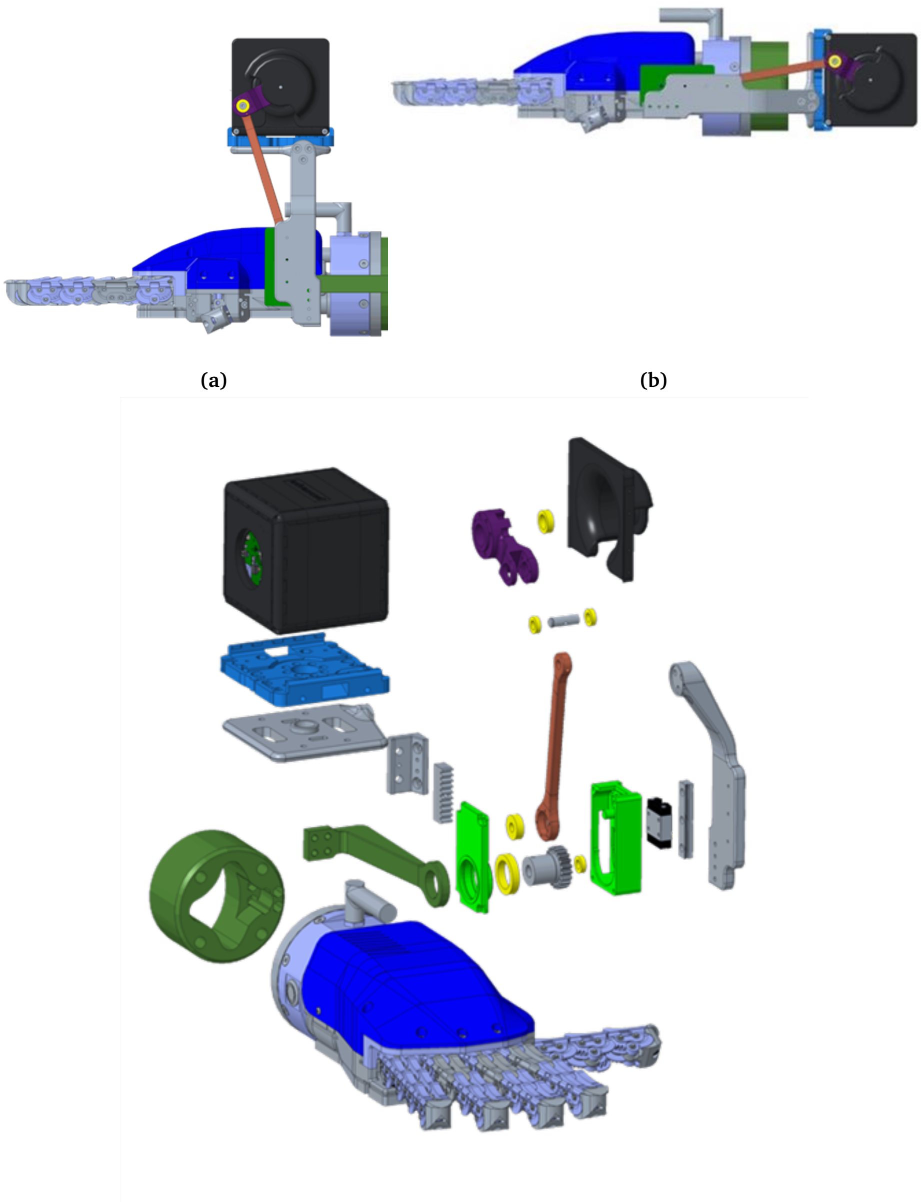
Figure 10: The new general purpose gripper mounted on a Franka arm in different configurations.

of rotation of the pinion and to a specific angular position of the pinion itself.

The SoftHand is connected via an ISO interface to the pinion, therefore having its absolute position and flexion/extension rotation depending on the specific position of the shaft of the QBMove Advanced.

It must be noted that, being the overall system a 1-DOF mechanism, also in this case the second degree of freedom of the qbmove Advanced can still be used to vary dynamically the stiffness of the mechanism, thus retaining the ability of the manipulator of performing complex and dynamic tasks.

As a final remark, from a communication and power supply point of view, the qbmove Advanced and the SoftHand can be connected separately to two different communication ports (Figure 13a). However, for simplicity, we also provide the gripper with an M8 to ERNI cable that connects the SoftHand with the qbmove Advanced and then from an ERNI to ERNI cable from the qbmove Advanced to the power supply (24 V). Finally, only one USB cable, is used to connect the chain made up of two devices (qbmove Advanced and SoftHand) to the pc of the DARKO robotic platform. This second choice allows to use only one communication port for both devices (see Figure 13b).

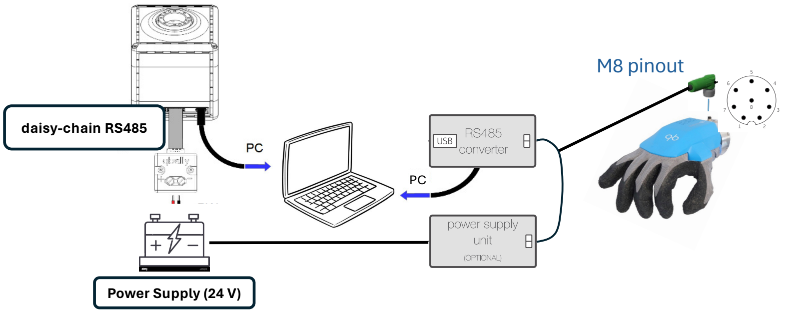


(a) (b)

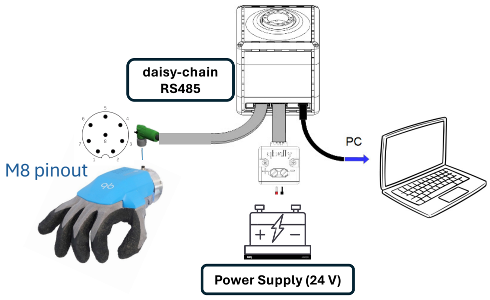
(c)

Figure 11: Layout of the latest general purpose gripper that consists of the SoftHand 2 attached to a Variable Stiffness Actuators by a slider-crank mechanism combined with a rack-pinion mechanism that guarantees more compactness while ensuring variable compliance.

Figure 12: A more compact version of the elastic wrist.



(a) The 2-serial port configuration from PC and the qbmove advanced plus SoftHand 2. Notice that, in this case, the power suplly is provided separately to the two devices.



(b) The 1-serial port configuration from PC to the qbmove advanced and from the latter to the SoftHand 2. Notice that the power supply to the two devices is obtained by connecting the battery to one of the Deisy-Chain RS485 (ERNI) port of the qbmove Advanced.

Figure 13: The two possible connection schemes of the new gripper.

3.1 Gravity compensation

Since the qbmove Advanced has an internal elasticity, it is necessary to introduce a static compensation of the gravity contribution due to the weight of the SoftHand that acts on the elastic wrist joint. The goal is to maintain the desired orientation of the SoftHand in spite of the weight of the SoftHand that acts on the elastic joint of the qbmove Advanced. The contribution of the angular gravity compensation θ_{gc} can be computed as a function of model parameters a_{mot} [1/rad] and k_{mot} [N· m], which depend on the geometry of the motor and the stiffness of cables, the nonlinear stiffness σ (see the data-sheet[3]) of the qbmove Advanced, and $G_{\text{wrist}}(q)$, which is the element of the gravitational torque vector related to the wrist joint, as follows:

$$\theta_{gc} = \frac{1}{a_{\text{mot}}} \cdot \left(\text{asinh} \left(\frac{G_{\text{wrist}}(q)}{2 \cdot k_{\text{mot}} \cdot \cosh(a_{\text{mot}} \cdot \sigma)} \right) \right) \tag{1}$$

From a theoretical point of view, $G_{\text{wrist}}(q)$ represents the torque applied by the inertia of the end-effector on the wrist joint and it can be computed as:

$$G_{\text{wrist}}(q) = \left(\bar{l}(q) \times m\bar{g} \right) \cdot \hat{k}(q) \tag{2}$$

where m is the mass of the end-effector, $\bar{l}(q)$ is the position of the center of mass with respect to the wrist joint expressed in robot base frame, $\bar{g}$ is the gravity acceleration vector expressed in robot base frame and $\hat{k}(q)$ is the versor of the wrist joint axis expressed in robot base frame. It is worth mentioning that the gravity contribution on the wrist joint axis can be obtained through the C++ KDL library (Kinematics and Dynamics Library).

4 Improvements of the pneumatic tool

To show the capability of our hand to also use a specific hand-tool, during the first period of the project, 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 the above-described challenging situations where objects are well-ordered next to each other. The pneumatic tool, which is equipped with a suction cup and a Venturi effect pump, can also be used for throwing objects by applying to the object a thrust force generated by a flow of pressurized air.

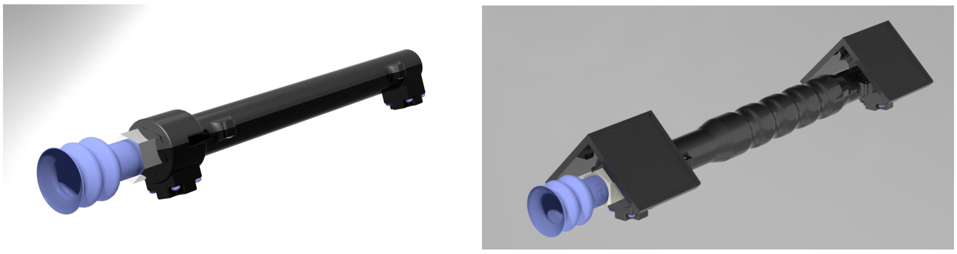
The hand tool is meant to be attached to the shelf structure to a pair of brackets through magnets in such a way that the multi-fingers gripper is able to grasp it. The hand-tool is mainly conceived and designed to be used by a robotic arm, on a fixed or mobile base, equipped with a multi-fingers gripper, such as the SoftHand research and the SoftHand 2, described in previous sections. 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.

In this second period of the project, our effort has been mainly directed towards 1) the submission of an Italian patent [1] , 2) the definition of the pushing model to have a more predictable throwing trajectory, and 3) improving the design of the tool to simplify the grasping of the hand-tool by the SoftHand.

4.1 Design improvement

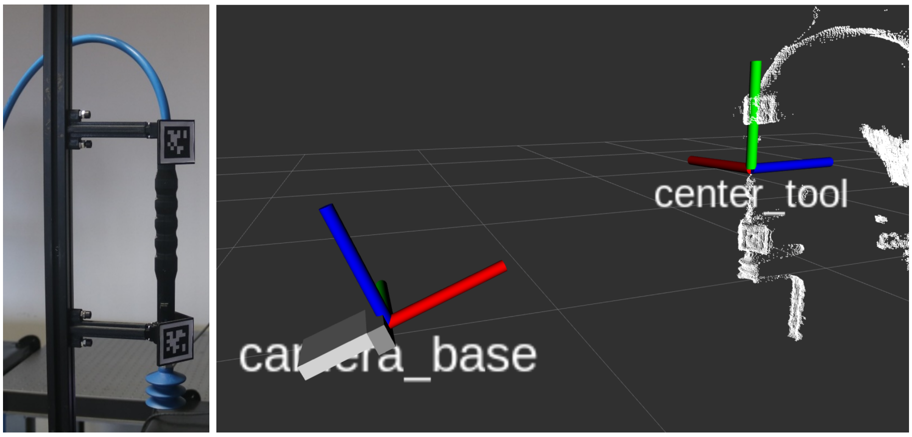
The novel design of the tool tackles mainly two problems: 1) improvement of the ergonomics of the handle related to grasping with the SoftHand, and 2) detection of the 6D

[3] https://qbrobotics.com/wp-content/uploads/2021/08/qbmove-Advanced-datasheet.pdf



(a) **(b)**

Figure 14: Comparison between the original (left) and the novel (right) mechanical design of the pneumatic tool handle.



(a) **(b)**

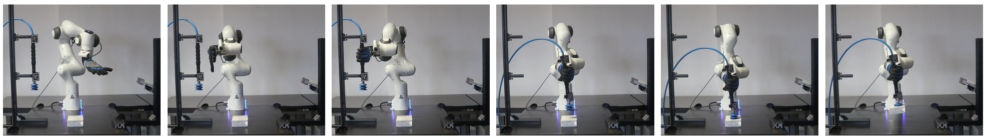
Figure 15: Estimation of the 6D pose of the tool with respect to the Franka arm base compared with the 3D point cloud measured by the camera.

pose of the tool with respect to the platform position.

Regarding ergonomics, the first version of the tool has a cylindrical handle with a constant diameter of 21 mm. However, the small diameter and the smooth surface of the handle do not help in achieving a stable grasp with the SoftHand. To improve the graspability of the tool, we have designed a new handle taking as examples the classical handles designed for human hands. The two main changes performed are increasing the average diameter, to obtain a better wrapping of the fingers around the handle, and designing the handle with different cross-sectional diameters (from a minimum of 24 mm to a maximum of 28 mm) to avoid slippage along the axis of the tool. A comparison between the new version of the tool and the older one is depicted in Figure 14.

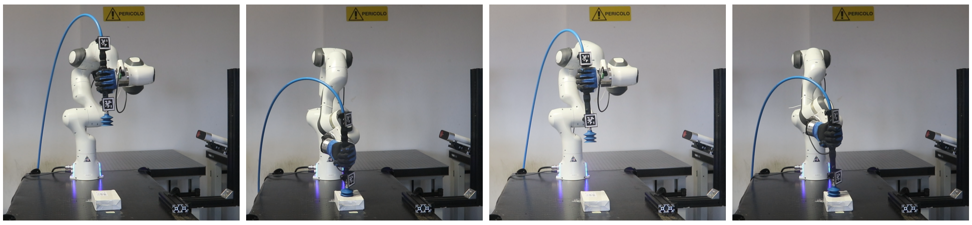
Regarding instead the 6D pose detection, we added to the structure of the hand-tool 4 AprilTag markers [4]. The integration of this system into the tool permits the estimation of the pose of the tool with respect to the base of the Franka arm (see Figure 15). The addition of this feature solves the problem related to the picking of the tool by the platform. In fact, given that the system is based on a mobile platform, we cannot rely only on feedforward information related to the position of the tool in the warehouse. With this solution, we can provide more reliable information to the arm planning algorithm to perform the tool-picking action.

Another problem that we can tackle with this type of information is the uncertainty related to picking up objects with the tool. In fact, given that we are using a soft gripper, it



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

Figure 16: Example of object picking using the pneumatic tool.



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

Figure 17: Testing of the in-had pose detection to compensate uncertainty in grasping. In the first two pictures (a-b) the tool is grasped near the suction cup, while in the last two pictures (c-d) the tool is grasped near the pipe.

is hard to know in advance the in-hand pose of the tool grasped by the SoftHand. However, this information is crucial to plan the motion to bring the suction cup in contact with the object to be picked. To overcome this problem, the solution proposed is to use the vision-based system to estimate the 6D pose of the tool after it is grasped by the SoftHand and compare it with the end-effector pose given by the kinematic of the manipulator. In this way, we can estimate the transformation matrix between the end-effector frame and the tool frame and we can integrate it into the kinematic chain to plan directly the Cartesian motion of the suction cup. In Figure 17, we can observe two tests where the tool is grasped differently by the SoftHand: one test is done taking the tool near the suction cup (a-b) and the other taking the tool near the other extremity (c-d). In both cases we can observe how the in-hand perception can compensate for this uncertainty permitting us to bring the suction cup to the right place to pick up the box.

The vision framework was tested in different conditions and some videos of these tests can be found at the following link[4]. The proposed system can provide a pose estimation also when only one marker is not occluded. However, given the high number of constraints in accomplishing the task, it is not straightforward to guarantee that at least one marker is always visible. For this reason, the next developments will be to investigate also markerless vision-based techniques for 6D pose estimation.

4.2 Pushing model

Regarding the model for the pushing action that the hand-tool exerts on the object, let us consider the simplified system depicted in Figure 18. Let assume that the inlet air pressure is enough to ensure air sonic speed at the final nozzle. The total mass flow $\dot{m}$ can be directly obtained from the exit area A, the inlet pressure P_0, and the fluid temperature T_0,

[4]https://unipiit-my.sharepoint.com/:f:/g/personal/m_baracca_studenti_unipi_it/EiUr3uJ4uLhKqhCfIh1KpZUBqRUQCcf7wjzMm4Abw51yrQ?e=rhuEj2

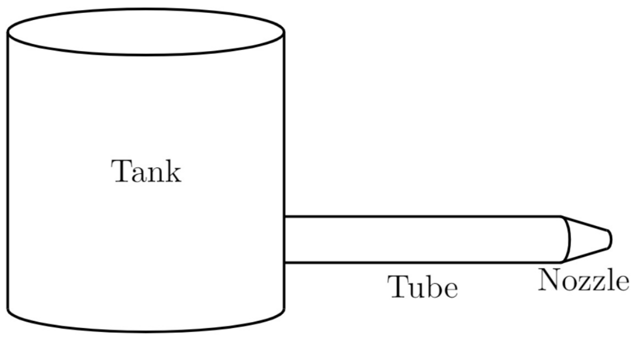


Figure 18: Scheme of the fluid-dynamics system for the air shoot.

i.e.,

$$\dot{m} = AP_0\gamma\sqrt{\frac{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}{\gamma RT_0}} \tag{3}$$

where γ is the air heat capacity ratio and R is the universal gas constant. Considering the Bernoulli equation with negligible potential energy

$$p + \rho\frac{u^2}{2} = \text{const}, \tag{4}$$

where p is the pressure, ρ is the air density and u is the air speed, and the mass flow continuity $\dot{m} = \rho Au$, the outlet density ρ and velocity u are obtained from the system

$$\begin{cases} \rho & = \frac{u^2}{2(P_0-P_f)} \\ \rho & = \frac{\dot{m}}{Au} \end{cases} \tag{5}$$

The force absorbed by the tool is

$$F_{\text{tool}} = \dot{m}u. \tag{6}$$

Finally, the force impressed on the object is obtained by the aerodynamic drag force, i.e.,

$$F_{\text{obj}} = \frac{1}{2}\rho uAC_{\text{d}}, \tag{7}$$

where C_{d} is a shape factor of the object to throw.

Due to the uncertainties in the model, we will make an identification procedure considering the parameters of the final throwing model. The final object velocity is obtained from the integral of the acceleration, with the hypothesis of the center of mass throw.

5 Conclusions

This report described the final prototype of the general purpose gripper that consists of two main parts: 1) a fast adaptive multi-synergy soft hand and 2) a one Degree of Freedoms (DoFs) elastic wrist that consists of a VSA. To further reduce the compactness of the wrist, we also propose a second version of the final gripper by reducing as much as possible the distance between the SoftHand itself and the shaft of the qbmove Advanced, for both the extremal configurations by means of a slider-crank mechanism. We also improve and finalize the ergonomics of the *pneumatic hand-tool*, which now can be grasped by the above-mentioned general-purpose gripper and used to simplify the picking up of objects in challenging situations in a more robust way. Moreover, a vision-based methodology has been developed for grasping and using the hand-tool by the Darko platform without resorting to an imprecise hard-coded configuration in the warehouse.

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