Title:	Self-reconfiguration of a robotic workcell for the recycling of electronic waste
Acronym:	**ReconCycle**
Type of Action:	Research and Innovation Action
Grant Agreement No.:	871352
Starting Date:	01-01-2020
Ending Date:	31-03-2024

Deliverable Number:	4.2
Deliverable Title:	First prototype of reconfigurable and adaptable soft end-effectors for electronic waste recycling
Type:	Demonstrator
Dissemination Level:	Public
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Estimated Date of Delivery to the EC:	31-03-2022
Actual Date of Delivery to the EC:	12-07-2022

Contents

Executive summary

Deliverable **D4.2** is a demonstration deliverable that contains videos showing the new features of soft end-effectors developed in ReconCycle. They were used in the disassembly process for the Kalo 1.5 heat cost allocator. The developed approaches are presented in two separate videos that can be viewed on YouTube:

- Video 1: The disassembly of the inner components of Kalo 1.5 heat cost allocator with new soft EE:

  YouTube link: https://www.youtube.com/watch?v=LpM5BWRLUac

- Video 2: New features of qb SoftHand 2 Research

  YouTube link: https://www.youtube.com/watch?v=tKnWyoWBwac

The disassembly workcell uses two collaborative robots, equipped with soft end-effectors. The first robot uses the qb SoftHand Research to easily grab the samples, place them in a vice, and then remove the empty frame at the end of disassembly sequence. The second robot is equipped with the variable stiffness gripper, which is able to unlock and safely remove the internal components of the device, thus avoiding a tool changing and waste of cycle time. The next step will be the implementation of qb SoftHand 2 Research, the evolution of the first robotic hand, currently used in the workcell.

1 The application of soft end-effectors in the ReconCycle project

The ReconCycle project aims at designing and implementing a self-configuring autonomous robotic workcell for the specific application area of electronic waste recycling, which so far has not reached any significant degree of automation. The automation of recycling processes by manual programming for specific models is insufficient to deal with a large variety of devices that need to be recycled. Adaptation of the recycling processes to different models or different devices is needed but this usually requires a complete reconfiguration of hardware and software. The diversity and model variety of electronic waste require flexible methods for recycling, so the main goal of the ReconCycle project is to introduce this type of flexibility into the robot workcell concept developed in previous projects such as ReconCell. The goal is to enable the automated robotic disassembly of different devices. The development of soft grippers / tools for disassembly (relevant to research objective O1 and O3 defined in the proposal) concerns the research and development of grippers and tools that support advanced disassembly skills in terms of adaptiveness, robustness, dexterity and reconfigurability. They need to be able to adapt to variations in the structure of different electronic devices.

The objective of WP4 is to develop adaptive and reconfigurable soft end-effector and simple flexible supporting tools, for the disassembly and management of electronic waste. The main outcome will be the next generation of handling tools characterised by advanced skills in terms of object adaptability, task flexibility, robustness in the interaction with uncertainties, manipulation capabilities for disassembly, fast reconfigurable kinematic configurations and reduced complexity w.r.t state-of-the-art of dexterous robotic end-effectors. Moreover, the developed grippers and tools with soft elements are able to deal with objects with variations in their size and shape while providing stable grasps, which is important when executing advanced disassembly tasks such as unscrewing, levering, breaking-in, cutting, etc.

In this document we present the upgrades of VSA gripper in terms of versatility and adaptability, applied to the use cases studied in the project. Grasping tests on components and parts of the heat cost allocator (HCA) samples have been carried out using both qbSoftHand Research and VSA gripper. The goal was to provide a broader view of soft end-effector capabilities.

Figure 1: qb SoftHand Research

2 qb SoftHand Research

qb SoftHand Research shown in Figure 1 is an anthropomorphic robotic hand based on soft robotics technologies; it is flexible, adaptable and able to interact with the surrounding environment, objects and humans while limiting the risk of hurting the operators, spoiling the products to be handled, and damaging the robot itself. It is adaptable and can grasp different objects without any change in the control action, showing an unparalleled level of simplicity and flexibility. This robotics hand has 19 kinematic degrees of freedom but just one degree of actuation, which is driven by just one motor. All the phalanges are connected to each other through a single wire, pulled from a motor placed on the palm thus closing the whole hand. This design follows the first synergy of a human hand. When the motor releases the cable, the elastic joints between the phalanges allow the opening.

The hand's closure is achieved by a 24 VDC motor that pulls the tendon passing through all the fingers. Releasing the tendon, elastic ligaments between phalanges open the hand. The user can directly control position and velocity of the motor and consequently the closure of the fingers, limiting the maximum grasping force by a controller on current consumption. For communication with the hand, the communication protocol is *RS485* has been made available. The *qb SoftHand Research* has been successfully integrated in the ReconCycle workcell by implementing a suitable *ROS node*. It has been employed to grasp example heat cost allocators and place them in the pneumatic vice and to pick up the plastic enclosure from the clamp after the removal of the inner components `https://www.youtube.com/watch?v=ltYug8picbI`.

3 qb SoftHand evolution

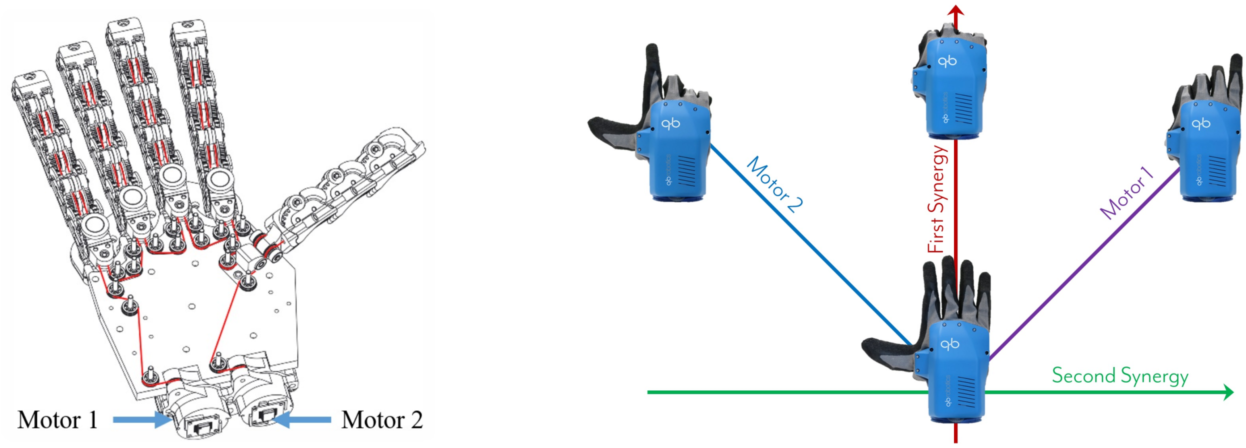

Figure 2: qb SoftHand 2 Research - transmission system with two motors. There is a single tendon passing though the hand, starting from a motor pulley up to the other one. The disposition of free pulleys on the palm, i.e. the layout of the transmission system, determines the kinematics of the whole hand.

The evolution of qb SoftHand is the *qb SoftHand 2*. The transmission system by a single tendon, the kinematic movements of joints, and the layout of fingers are the same as in the original qb SoftHand Research, which was used as a starting point. In the successor model qb SoftHand 2, the friction of transmission system and the introduction of a second motor allow

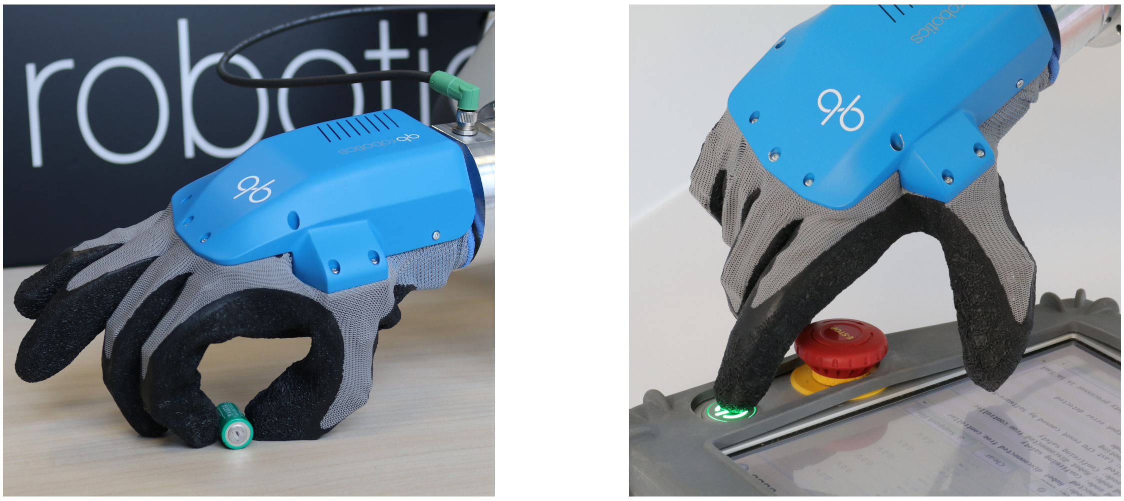

Figure 3: qb SoftHand 2 Research – main features.

the hand to realize several postures of fingers by exploiting the combination of movements of the two driving pulleys (see Figure 2). With this design we added the second synergy of the human hand. We can generate multiple postures as a combination of the first and the second synergy [1][2]. This robotic hand can manipulate objects without changing the wrist orientation, perform a precise grasp and apply localized contact forces. The new skills, especially the more precise "pinch grasp", allow for better grasping of small objects such as batteries (see Figure 3) that are often installed in electronic devices that need to be disassembled. The ability to grasp larger objects has been preserved.

4 VS gripper

While five finger hands like qb SoftHand are versatile and effective, in ReconCycle we are interested also in simpler and inexpensive soft grippers. The *qb Soft Gripper* shown in Figure 4 is a compact, light and versatile variable stiffness gripper. While not providing all the functionalities of five finger hands, it can be effectively used for many disassembly tasks.

The gripper consists of two fingers. The *mobile finger* is driven by the *qbmove Advanced*'s shaft, thus it can perform a soft movement to grasp objects while avoiding damage to critical

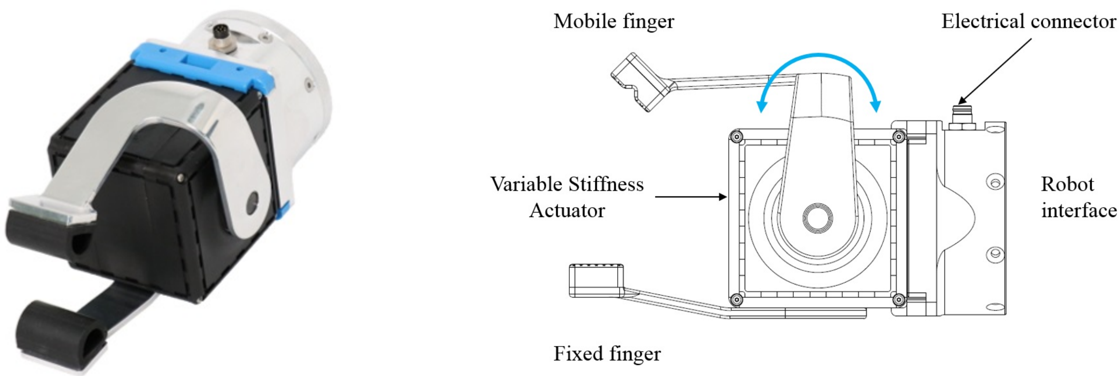

Figure 4: Variable stiffness gripper developed in ReconCycle

Table 1: qb Soft Gripper main data. *Force* values are evaluated by tests with a load cell mounted on the fixed finger, grasping objects of different dimensions. k indicates the stiffness of the pad's centre, tangent to the closing trajectory and evaluated from the torsional stiffness of *qbmove Advanced*.

Data	**value**	**[unit]**
$Force_{min}$	0.5	$[N]$
$Force_{max}$	64.0	$[N]$
k_{min}	0.07	$[N/mm]$
k_{max}	11.5	$[N/mm]$
$Closingtime$	0.5	$[s]$
$Dimensions$	81x90x165	$[mm]$
$Weight$	0.78	$[kg]$

parts. It can also apply stronger grasps by increasing the stiffness. On the other hand, the *fixed finger* is directly connected to the frame.

Variable stiffness systems have been designed to overcome the limits of conventionally actuated robots in terms of safety in human robot interaction and for operating in an unstructured environment. They can be seen as systems with a nonlinear transmission that transforms input torques and velocities of its prime movers into a set of four new variables relative to the output shaft: torque, velocity, stiffness and stiffness velocity. The basic characteristics of qb Soft Gripper are shown in Table 1.

4.1 Control modalities

A low-level controller has been implemented on-board. It controls motor positions θ_1 and θ_2 (see Figure 5) according to the reference inputs: the preset stiffness and the equilibrium position of output shaft. When the two pulleys rotate in the opposite directions, the nonlinear

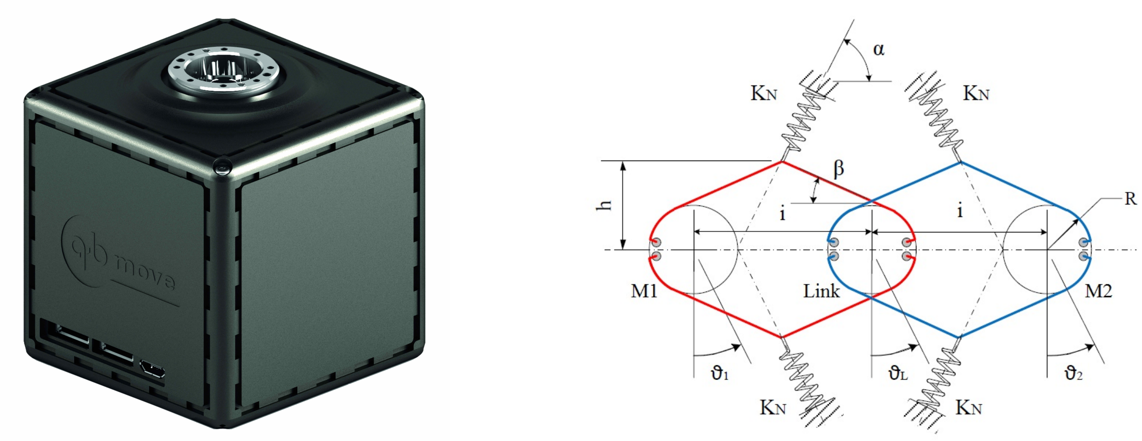

Figure 5: The variable stiffness mechanism that permits the implementation of human-like behaviours. The geometrical disposition of linear springs and tendons implements the non linear characteristic of the agonist-antagonist mechanism in the qbmove. The three circles indicate the two motors and the output shaft in the middle.

springs become loaded. This results in the change of their working point and thus in a different stiffness. Since the two transmission systems have the same characteristics, this movement does not change the output shaft equilibrium position in the absence of the external load. Conversely, pulley rotations in the same direction move the output shaft equilibrium with no load. The gripper is able to grasp objects of considerable disparate nature, exploiting the intrinsic mechanical intelligence of its variable stiffness system, without using any type of sensors on the contact surfaces or specific algorithms to control the motors. These aspects make it a versatile, light, economical and easy-to-use device. The gripper can be basically controlled in two ways:

- position-stiffness control;
- deflection control;

In the first modality, the user directly controld the finger position and the grasp stiffness according to the nonlinear behaviour of the VS system. In this way it can obtain a precise grasp and pre-grasp, setting the stiffness according to the object's fragility. However, in order to obtain the grasp with desired stiffness, the object's dimensions have to be known first. On the other hand, in *deflection control* we can set the maximum deflection between the link position θ_L and the equilibrium position $(\theta_1 + \theta_2)/2$, which enables us to fully close the finger. In this way we can set the maximum applied force on the object regardless of its size. The *deflection control* is the most appropriate modality for the ReconCycle use cases, due to the variety of shapes and dimensions of electronic devices.

5 VS gripper features

The gripper offers many possibilities regarding the finger geometry and interfaces. In particular, analysing the possible shapes of the pads and considering the *fixed finger* as a "tool", this point of view opens up interesting features such as:

- smart finger-pads exchange system,
- tool exchange system without motors or pneumatic components, and
- design of different tools for disassembly (big and small screwdrivers, different levers, hooks, etc.);

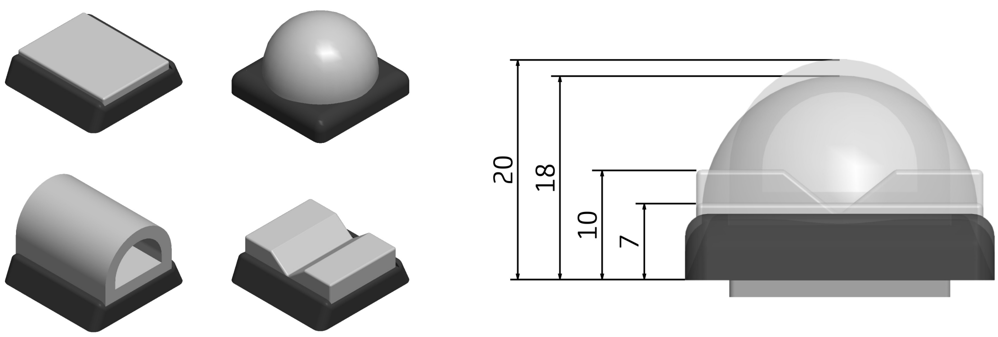

Figure 6: Set of soft pads and their thickness [mm]

An easy way to connect two small elements without pins or screws is by magnets. In this solution, both fixed and mobile finger can be equipped with different kind of pads. An easy and quick substitution is obtained by magnetic elements. Figure 6 shows a set of soft pads with different dimensions and shapes among which to choose the most suitable for the task.

5.1 Pad exchange system

This magnetic system allows for an easy setup the gripper with the desired kind of soft interface and easy maintenance. The pads are designed to also allow the assembly without magnets by utilising screws instead. This way we can avoid any possible issues coming from the magnetic forces.

5.2 Tool exchange system

The design of a tool exchange system starts by dividing the fixed finger into two parts: the *housing* connected to the qbmove Advanced and the removable *finger tool*. The interface between these components is designed to allow the free insertion of the finger tool into the housing and its locking in a certain configuration without using any screw, pin or tool. Figure 7 shows the assembly sequence of the tool exchange system: insertion (1), rotation (2), and locking (3).

The *finger tool* is axially constrained thanks to the two wings. The rotation is prevented by a special shape mounted in the *housing*, where it is pushed by a compression spring. In order

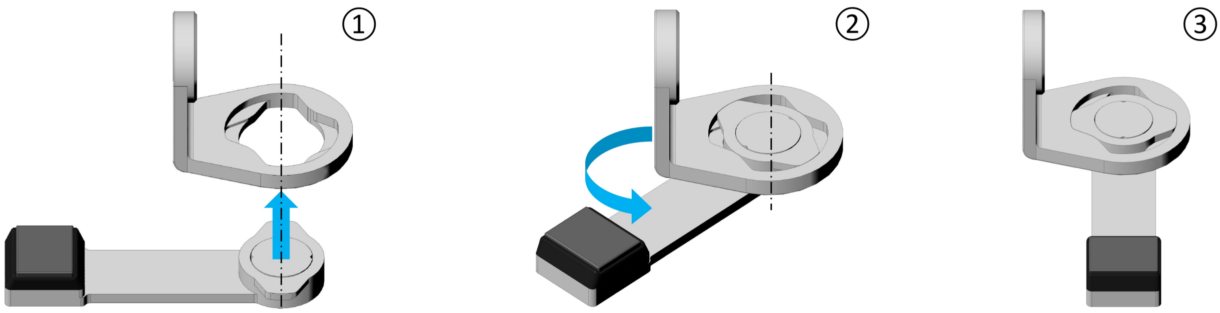

Figure 7: Finger tool assembly sequence

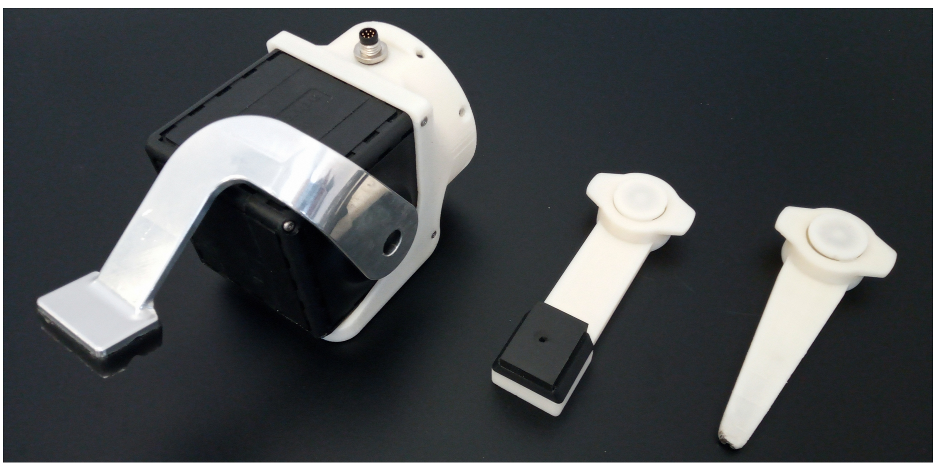

Figure 8: VSA gripper with the tool exchange system and different tools

to obtain the free rotation, one has to apply an external force able to compress the spring; then s/he can rotate and remove the finger tool.

The tool exchange system offers different design possibilities for the finger tool. This gives us the possibility to develop well suited tools for different disassembly operations as shown in Figure 8.

6 Demonstrator

The first realization of the ReconCycle workcell with two Franka Emika Panda robots is shown in video https://www.youtube.com/watch?v=ltYug8picbI. qb SoftHand Research is mounted on *Robot A* and a pneumatic tool changer (screwdriver + pneumatic gipper) on *Robot B*. The disassembly sequence shown in the video can be summarised as follows (*IN* indicates the inner component of HCA):

1. picking up the device and its positioning in the clamp; (Robot A)
2. levering to remove the inner structure *IN*, i.e. device without the external frame; (Robot B)
3. exchange of tools for picking and positioning of *IN* in the cutter; (Robot B)
4. grasping of the battery; (Robot B)

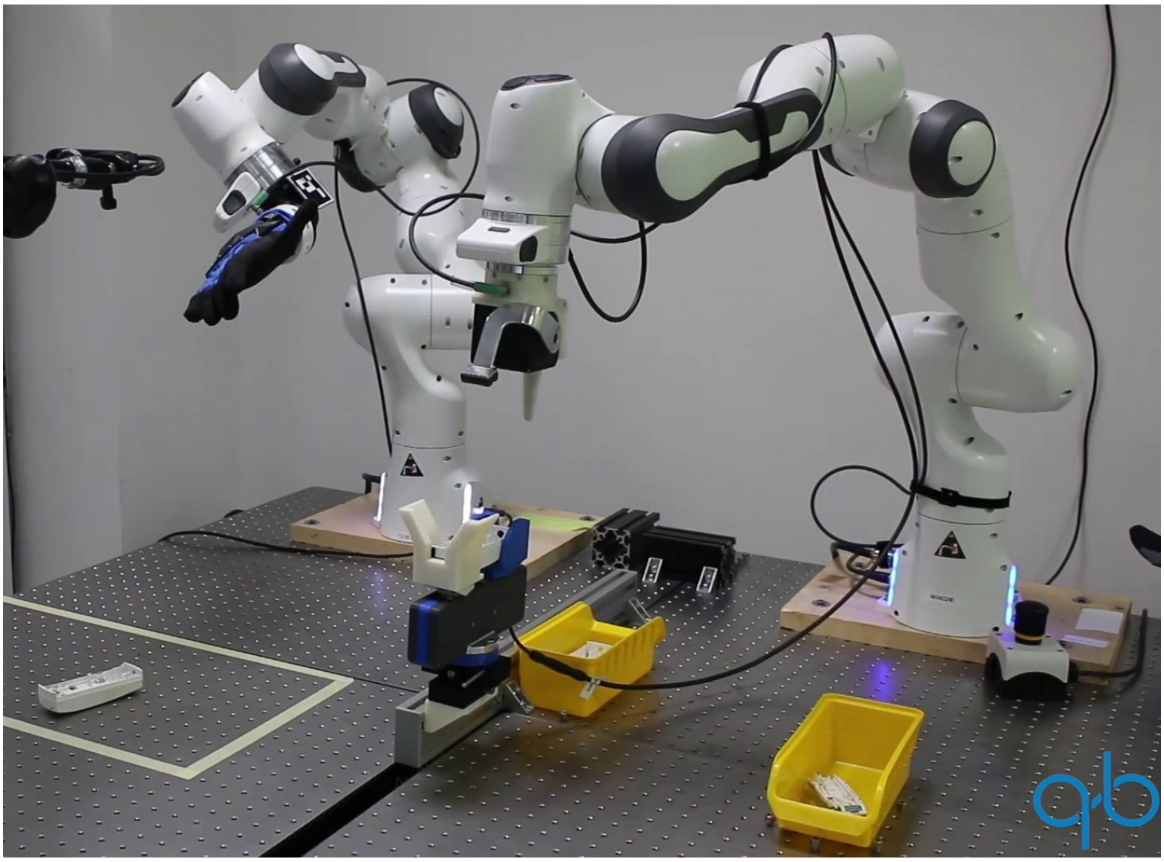

Figure 9: Demonstrator with new end-effectors

5. grasping of the external frame during the tool changing between phase 2 and 3; (Robot A)

Our aim was to obtain a new disassembly sequence to reduce the cycle time, exploiting the capabilities of the newly developed soft grippers. The new configuration includes qb SoftHand 2 Research mounted on *Robot A* and a VS gripper mounted on *Robot B*. The first step to validate this upgrade was a demonstrator that exploits these new capabilities, e.g. those of the VS gripper that is able to apply localized forces for the removal of internal components and their subsequent grasping, without the need to change the end-effector.

Using ROS as the software platform for integration, the new demonstrator with two Panda robots has been implemented (see Figure 9). It includes a robot equipped with qb SoftHand 2 Research to grasp the heat cost allocators, place them in a vice, and then remove the empty frame. The second robot is equipped with the variable stiffness qb Soft Gripper, which is used to quickly detach and remove the internal components of the electronic device while avoiding the tool change, as shown in Figure 10.

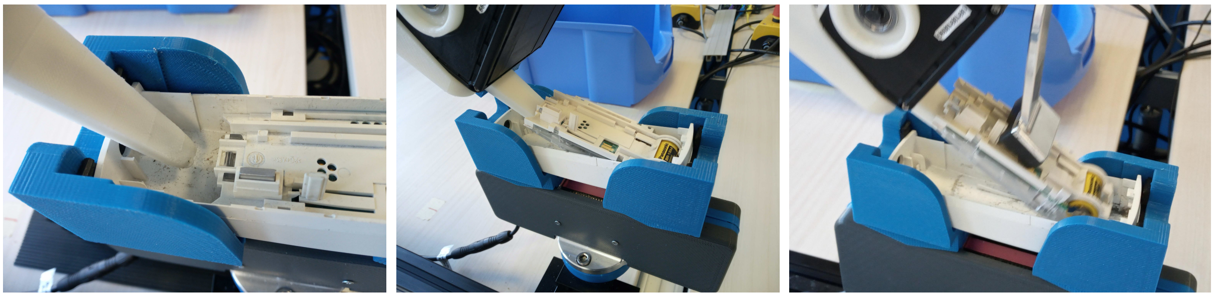

Figure 10: Levering sequence to remove the inner part of the heat cost allocator: 1. approach motion, 2. inner part detachment using the roll movement, and 3. grasping and picking up the HCA.

The video of this demonstrator is available on the ReconCycle video channel and also at https://www.youtube.com/watch?v=LpM5BWRLUac.

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