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Contents

Executive summary

Deliverable **D5.5** is a demonstration deliverable that contains videos showing the implementation of the disassembly process for different smoke detectors.

We previously presented an adaptive disassembly process for different heat cost allocators, outlined and demonstrated in deliverables **D5.1**, **D5.2** and **D5.4**. By employing the adaptation and self-reconfiguration capabilities of the workcell, we were able to disassemble different devices from the same family. In this deliverable, we present a similar workflow that supports a different family of devices, i.e. smoke detectors.

The general disassembly workflow has been evaluated with two different smoke detectors, the Fumonic 3 radio net and Hekatron. An alternative workflow suitable only for a subset of the available smoke detectors was implemented for the KaloREMOTUS smoke detector.

The first video shows disassembly of the Fumonic and Hekatron smoke detectors. In both cases, the smoke detectors are placed within the CNC machine, where the top part is cut off. In the case of Fumonic, the battery contacts are also milled away by the CNC machine, while for Hekatron, the battery cover is first removed by the robot. In this smoke detector, the battery is soldered so that the contacts are very close to the battery and difficult to mill away using the CNC machine. Therefore, a rocking action is used to remove the battery from the contacts.

The second video shows the opening of the KaloREMOTUS smoke detector using several soft components, including SoftHand and two variable stiffness grippers.

The developed approaches are demonstrated in two separate videos, which can be viewed via the links provided below.

- **Video 1**: ReconCycle modular robotic workcell performing the disassembly of different smoke detectors by employing a CNC threadmill:

  Link: http://reconcycle.eu/videos/d5.5/smoke_detector_battery_removal_cnc

- **Video 2**: Opening a smoke detector by levering using a variable stiffness gripper:

  Link: http://reconcycle.eu/videos/d5.5/smoke_detector_opening_levering

1 Introduction

The aim of the ReconCycle project is the development and implementation of an adaptable and reconfigurable electronic waste recycling process. In the current recycling plants, electro-recycling is mostly performed following the "crush-and-separate" method, where devices are crushed and split into tiny particles, which are then physio-chemically separated into reusable components. However, this approach requires manual work if disposed devices contain dangerous components or parts that need to be removed before the rest of the device can go into the crusher. This can be stressful and repetitive for human workers. In the previous deliverable **D5.4**, we presented a solution for an automated disassembly of a variety of heat cost allocator (HCA) devices. Various skill-adaptation methods and reconfiguration possibilities of the recycling workcell have been explored.

In this deliverable, we demonstrate a disassembly protocol for a different family of devices, i.e. smoke detectors. We selected and analyzed a number of different smoke detectors and developed an adaptable solution that can disassemble different smoke detectors (see Fig. 1).

While we could reuse some of the hardware and methodologies that were developed for the disassembly of HCAs, some new solutions were nevrtheless required. We extended the vision system to detect smoke detectors and their locations, as well as utilized some new end-effectors in the disassembly pipeline, namely the three-finger centric Schunk gripper and the vacuum gripper. Another important addition is the CNC milling machine, which is used to open the housing of the smoke detectors. The disassembly workflows for three different smoke detectors are described in more detail in Section 3 and depicted in Fig. 4. The disassembly procedure was implemented inthe ReconCycle workcell at JSI for two different smoke detector devices, where various adaptation steps were taken. The disassembly sequence is demonstrated in **Video 1**.

In addition, we explored the possibility of combining stiff and compliant support elements as well as variable stiffness actuators to develop an alternative solution for opening the smoke detectors using levering at IIT. This approach is demonstrated in **Video 2**.

2 Analysis of different smoke detector types

We performed a detailed analysis of different smoke detector devices to determine the common features between them and to motivate the choice of tooling and disassembly procedures. Three different smoke detector devices are shown in Fig. 1.

The smoke detectors are all round or cylindrical in shape, with a diameter between 90 and 120 mm and a height ranging from 25 to 60 mm. Due to the smoke detectors' cylindrical shape, multi-finger centric grippers provides a possible solution to grasp them firmly.

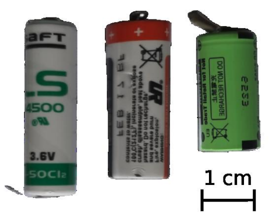
The different parts of smoke detectors (main body and cover) are held in place using either screws or plastic tabs, which lock the housing together. In the case of being connected with screws, 2-4 Phillips, Torx or Hex head screws are used. Screws of sizes M3 to M4 are most often used, which means that the screw head diameter is between 4.5 (for M3 screws) and 5.5 mm (for M4). Since they are relatively small, accurate vision information is required if unscrewing operation should be performed. The disassembly of smoke detectors that are held in place by plastic tabs is difficult to perform by a robot without a dedicated tool. Tabs tend to require both high forces to remove, as well as accurate robot gripper positioning. For the housings that do not require excessive forces to open, we explored the possibility of using a variable stiffness gripper to hold the smoke detector in place, similar to what a human would do, while a robot

(a) Smoke detector Fumonic 3 Radio Net

(b) Smoke detector Hekatron

(c) Smoke detector KaloREMOTUS

Figure 1: Front, back and internal views of different smoke detectors



(a) Examples of batteries.

(b) Wired (left) and soldered (right) battery connections.

Figure 2: Example batteries found in smoke detectors

performs the levering action.

Levering and unscrewing operations are not always an option to open smoke detectors. In some cases, multiple tabs need to be pressed at the same time, which is challenging to achieve with a general solution. Instead, a device-specific solution is often required. For this reason, we looked also at other options for opening the smoke detector housings. To achieve generality, we integrated a CNC mill into the proposed reconfigurable recycling cell.

We observe a variety of battery types being used in smoke detectors. The batteries can be either button-type (CR 2032), AA-type (LS 14500 or CR 17450), while in other cases, cell packs of lithium batteries (such as 3CR2) are used. Some examples of batteries are shown in Fig. 2a.

The removal steps for these different types of batteries can vary considerably. Button-type batteries are replaceable and not soldered in place, therefore they can be removed with a vacuum suction gripper. However, the AA-type batteries are usually soldered in place, as shown in Fig. 2b. This means a considerable force is required to remove them, so the contacts must be removed in some other fashion.

Cell packs of lithium batteries are also complicated to remove. In most cases, the batteries are connected to the device via wires, as shown in Fig. 2b. Cutting them requires care, as cutting both wires simultaneously can lead to a short-circuit and fire. In addition, the cell packs are usually epoxied into the plastic cover of the smoke detector, making them difficult to remove even for a human.

3 Adaptive disassembly process for smoke detectors

We defined disassembly workflows for three different smoke detector models. Several adaptation techniques were applied in the disassembly process, where some of them had also been used for heat cost allocator disassembly:

- Vision-based action prediction for determining the next step required to disassemble the smoke detector (used also for heat cost allocators). This includes the smoke detector's pickup location and the location of battery that needs to be extracted, the selection of the appropriate opening procedure (cutting, unscrewing, levering), etc.
- Adaptive grasping of smoke detectors with a three-finger centric gripper.
- Adaptive cutting process to cut the top of the smoke detector housing and expose the battery.

The workcell layout has been modified compared to the one used for the disassembly of heat cost allocators in **D5.4**. We removed the cutter and vise modules, while a new CNC module (see Fig. 3) was integrated. Additionally, a tool changer was added to one of the robots to allow switching between different end-effectors during the disassembly cycle. The version of the workcell for the disassembly of smoke detectors thus has the following modules:

- *Material Input Module*, where the smoke detectors are supplied.
- *Robot Module* with the Franka Emika Robot and a tool changer, enabling attachment of multiple end-effectors.
- *Robot Module* with the Franka Emika Robot and the qb Variable Stiffness Gripper (VSG).
- *CNC Module* with a computer numerical control (CNC) milling machine for the removal of smoke detector housing.

Figure 3: Workcell layout for smoke detector disassembly

See deliverable **D1.2** and reference [1] for more details about the modular hardware platform. The modules were integrated into the ReconCycle ROS network as described in deliverable **D1.1** and reference [2].

3.1 Disassembly workflows for smoke detectors

The workflows for two different smoke detectors are illustrated in Fig. 4, where different possible steps are shown based on the detected type of the smoke detector.

Since the smoke detectors are cylindrical, a three-finger industrial pneumatic gripper (shown in Fig. 5) can be used to grasp them robustly. This type of grippers is designed for grasping cylindrical objects. In addition, the three fingers move uniformly, which ensures that at the end of the grasping process, the smoke detector is centered within the gripper.

To maximize the number of different smoke detectors that can be grasped, it is beneficial that the gripper has a large stroke. We selected the Schunk PZH-20 gripper, which has a stroke length of $s = 20$ mm. Custom fingers with a specific offset from the center can be designed for the gripper, so that smoke detectors of a wide range of diameters can be grasped. However,

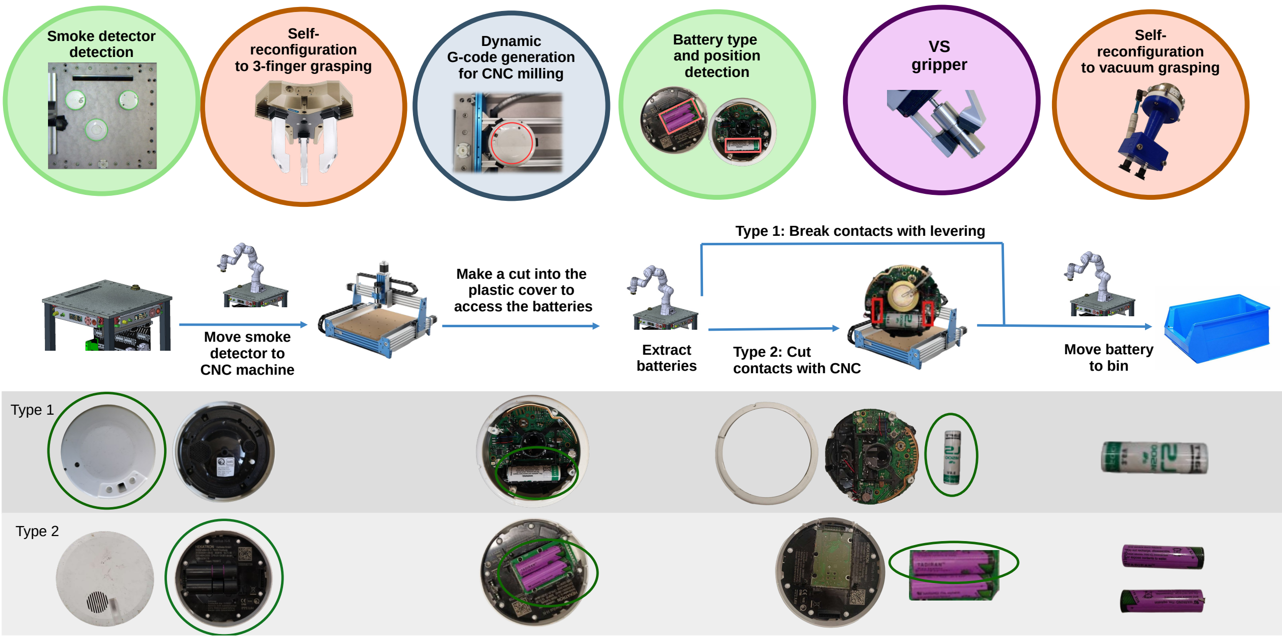


Figure 4: Disassembly workflow that employs the concept of self-reconfiguration and adaptation for two different types of smoke detectors. In the top row, the reconfiguration and adaptation features are highlighted. Green circles show vision-based adaptation. Orange circles show hardware self-reconfiguration. A purple circle shows soft-robotics based approaches. A blue circle shows dynamic G-code generation based on the geometry of the current smoke detector. The two bottom rows show which parts are being manipulated at different stages of the workflow.

it is not possible to grasp all smoke detectors without finger exchange if the diameter of the considered smoke detectors vary by more than the stroke length of the gripper.

Two of the workflows (for smoke detectors of the type Fumonic and Hekatron) utilize the

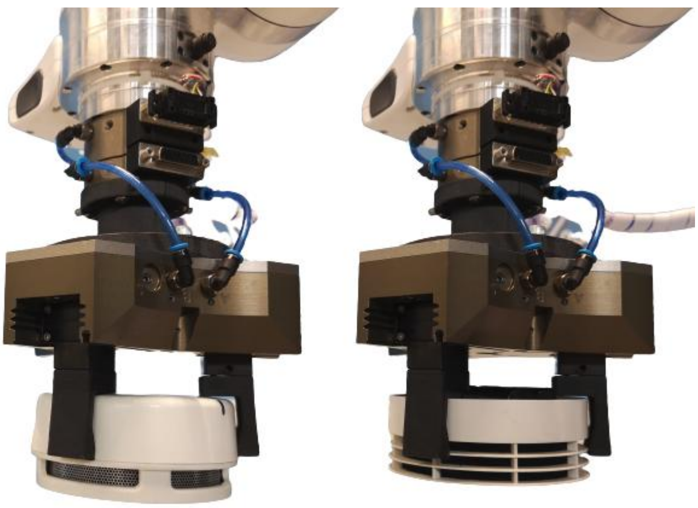


Figure 5: The Schunk PZH-20 robot-mounted gripper gripping Fumonic (left) and Hekatron (right) smoke detectors

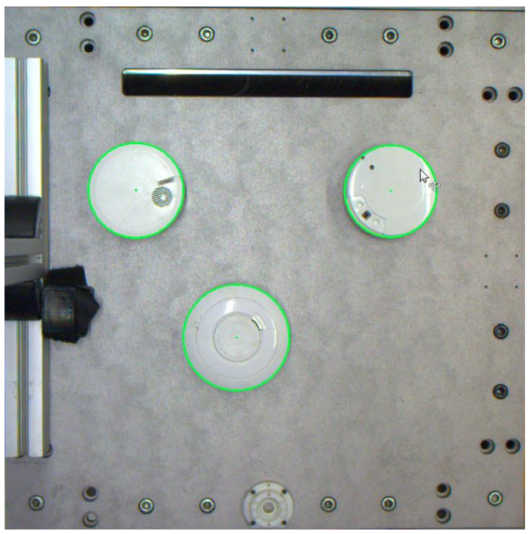


Figure 6: Detected locations of different smoke detectors on the material input module using machine vision

CNC milling machine (detailed in Sect. 3.3). The CNC machine is used to cut off the top cover of the smoke detector and expose the battery. The workflows differ in the way the battery is extracted. In the case of the Fumonic smoke detector, the CNC machine mills off the battery contacts and the battery is removed using a vacuum gripper. For the Hekatron smoke detector, the battery is removed by levering. In both cases, after battery removal the smoke detector plastic housing and PCB are grasped using a three-finger gripper and placed into the waste bin.

During the disassembly pipeline, vision is utilized at several steps, i.e., to detect the smoke detector location for pickup, to detect its orientation for CNC milling, and to detect the battery location for extraction.

3.2 Vision-based action prediction

At the start of the disassembly cycle, we employ machine vision to detect the location of smoke detectors on the Material Input Module (some examples of the detected parts are shown in Fig. 6) and transport them to the CNC Module. Vision is then further used to detect battery location and predict the optimal extraction method and to determine whether each of the disassembly steps has been successful.

3.3 Dynamic CNC milling

Since there are many different types of smoke detectors that cannot be all opened using levering or unscrewing operations, we decided to integrate into the workcell a CNC milling machine. The CNC machine is used to cut a desired shape into the housing of the device that is being disassembled. This removes the need for complex operations, such as unscrewing or precise levering at multiple locations.

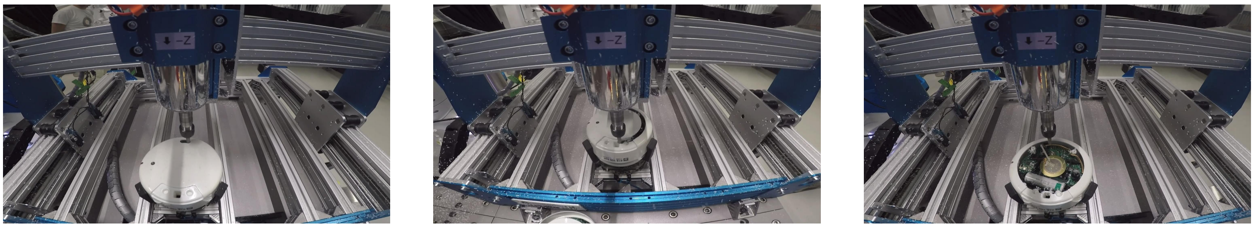
We employed an off-the-shelf CNC milling machine Genmitsu PROVerXL 4030. It operates based on input G-code, which specifies the sequence of milling operations. The initial G-code program is generated by an application engineer using an off-the-shelf CAD/CAM program, such as PTC Creo or FreeCAD. The engineer decides which parts to cut based on the smoke detector's geometry and battery position within the smoke detector's internals. The G-code is designed for a single fixed pose of the smoke detector. If the position or orientation of the smoke detector changes, the path described by the G-code is dynamically translated and rotated based on the information provided by the vision system.

The commands for milling operations are sent via ROS interface. We implemented a ROS action server in Python that accepts G-code commands and sends them to the CNC machine in order to perform the desired milling operations. Thus the CNC machine is integrated into the cell's ROS network just like any other peripheral device.

The milling of plastic parts can produce a considerable amount of debris. To reduce the quantity of debris after milling, the CNC machine has a vacuum cleaner adaptor placed next to the mill. A vacuum cleaner can be connected to this adapter and used to vacuum the debris as the milling operation is being performed.

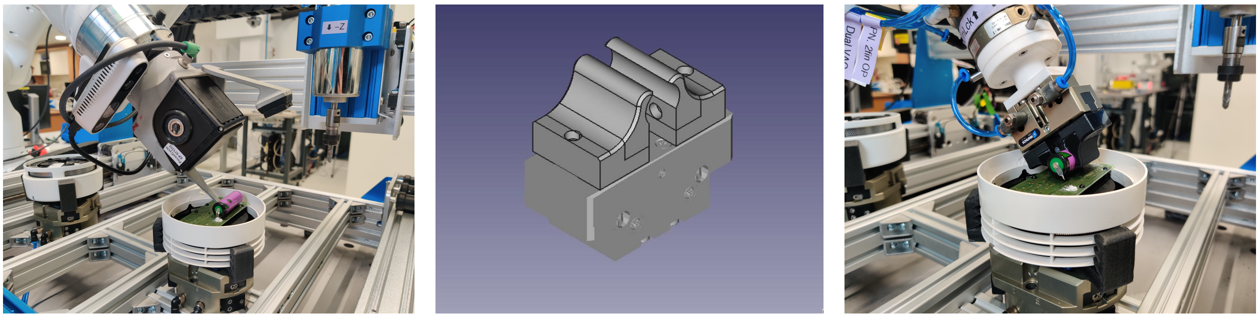
3.4 Battery extraction methods

The smoke detector type and shape is detected by the vision system using a neural network, as presented in **D2.1** and **D2.2**. The aforementioned three-finger centric gripper is used to



(a) Initial cut. (b) Cutting. (c) Smoke detector top removed.

Figure 7: Cutting off the smoke detector top using the CNC machine



(a) Variable stiffness gripper with a levering tool (b) CAD model of a specialised gripper (c) Battery removal with a specialised gripper

Figure 8: Battery extraction

reliably grasp and center the smoke detector within the gripper.

The robot then transports the smoke detector into the CNC milling machine, where it is securely clamped within a similar three-finger gripper as the one used on the robot. The CNC machine performs the milling to cut out the plastic part above the battery, as shown in Fig. 7.

Depending on the smoke detector type, the battery is connected to a PCB mounted within the considered smoke detector in a variety of ways (see Section 2 above). We currently use an eye-in-hand camera to detect the battery position and the connection type.

After the battery has been detached from the rest of the smoke detector's internals, the battery can be either levered out using the variable stiffness gripper with a levering tool (see Figure 8a) or lifted using the vacuum suction gripper, before being transferred to a bin for batteries. In addition, the levering action and battery removal can be performed by a specialised gripper (see Figure 8b and 8c). The residual plastic case and internals are also transferred to a dedicated bin.

4 Opening of a smoke detector using stiffness adaptation and levering

Some smoke detectors, e.g. KaloREMOTUS model, can be opened by applying a levering operation. The automation of this procedure is a challenging task that demands expertise unique to human operators. Upon observing human operators, it can be noticed that they utilize a technique of levering the lid out while applying pressure to the device against a rigid surface, such as for example a worktable, with their hand as a second yielding opposing surface (see Fig. 7 in deliverable **D5.1**). This technique allows the operator to insert a tool into the narrow gap of the device while relying on an opposing rigid surface to counteract the resulting forces. In doing so, their hand does not hinder the lid from deforming and eventually sticking out. While traditional robotics is not well-suited for this human-specific approach, soft robotics can effectively simulate the actions of a human operator.

To demonstrate the effectiveness of a compliant approach, we built an experimental setup depicted in Fig. 9. This experimental set up was constructed using the available equipment

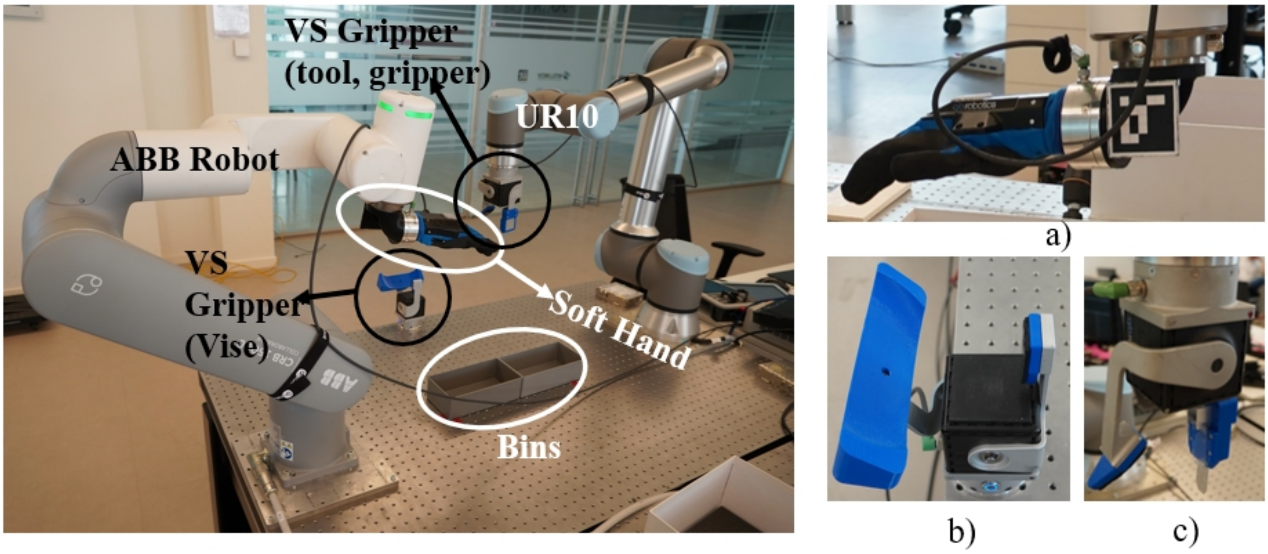


Figure 9: Setup for the opening of smoke detectors using the levering action

present at the JOiiNTLAB of IIT in Bergamo. It consists of the following robots, grippers, and tools:

- a VSGripper that functions as a bench vise featuring a fixed finger and a specially designed template pedestal for the smoke detector as shown in Fig. 9b,
- a VSGripper on a Universal Robot UR10 with a specially designed tool attached to the fixed finger, illustrated in Fig. 9c,
- a SoftHand on the wrist of an ABB Robot, as shown in Fig. 9a,
- two bins for collecting the disassembled parts.

The objective of the demonstration was to provide a suitable dismantling sequence and end-effector parameters in order to successfully detach the smoke detector lid from the rest of the device. This step is considered the most challenging subtask of the overall disassembly process for smoke detectors. Once the lid is removed, the battery can be easily accessed. Fig. 10 illustrates the sequence the robots followed to perform the removal of the lid.

The aforementioned sequence was performed using low-level position control where way-points were manually set in the Cartesian space. Once the way-points were specified, the robots followed the trajectories generated by linear and spherical interpolation, respectively, to achieve the required translation and orientation of the end-effectors. In order to effectively

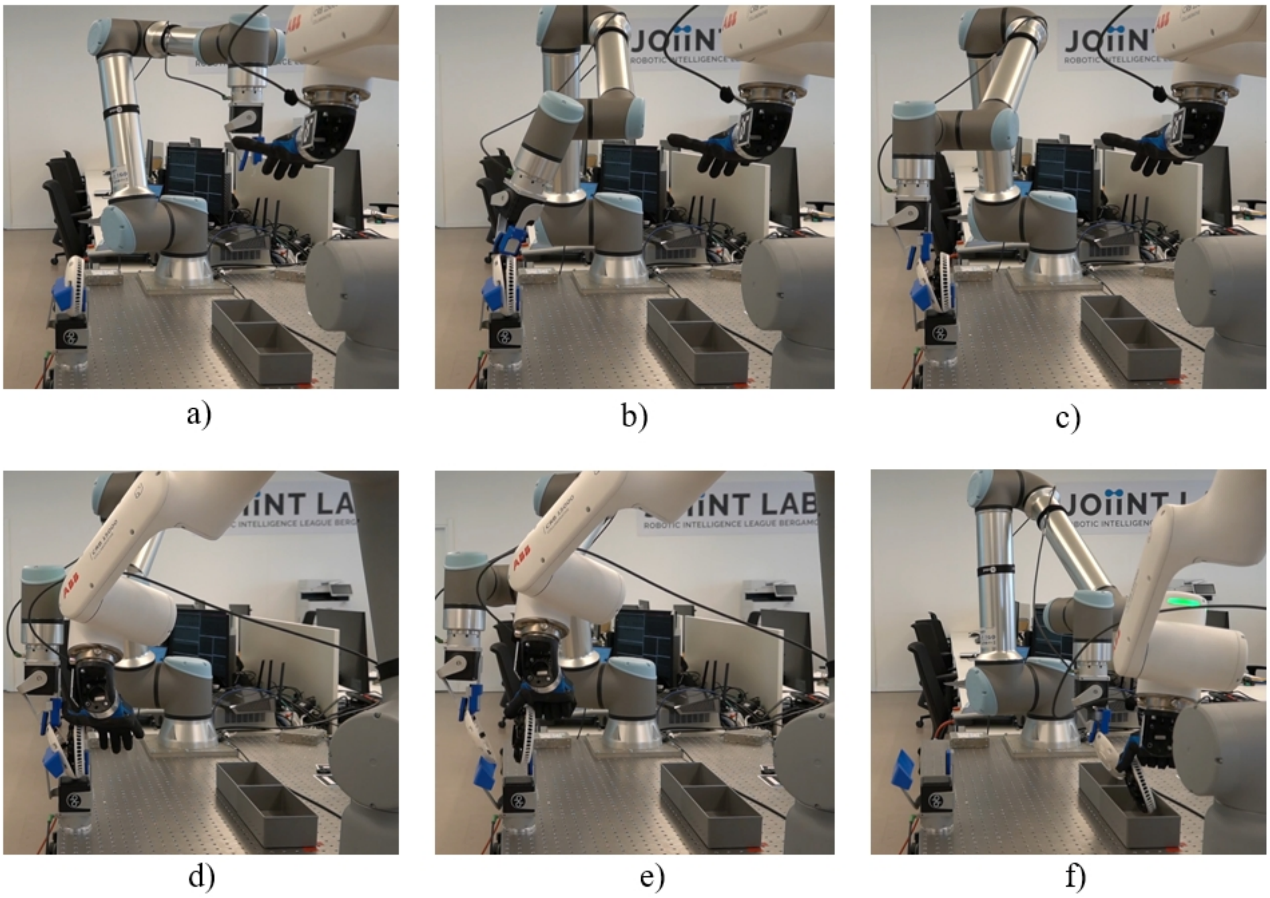


Figure 10: A sequence of actions to perform the removal of the lid of the smoke detector: a) The device is manually positioned onto the open soft vise. As the vise closes, the special shape of the template securely clamps the smoke detector into a precise position. b) A custom-made tool attached to the fixed finger of the mobile VSGripper is forced to enter the narrow gap present on the device. By applying controlled twisting motion to the tool within the gap, the small wings that hold the lid attached to the rest of the device are disengaged. c) Leveraging the compliant behavior of the soft vise, the smoke detector can be opened by pushing the lid against the template on the mobile finger. This action exposes the internal space of the device for the final complete disassembly. d) Leveraging the compliant nature of the SoftHand, the thumb can be pushed against the rear of the tool and effortlessly inserted into the previously created gap. e) Once the VSGripper and the SoftHand are closed, the soft vise opens allowing the end-effectors to completely separate the lid from the remaining part of the device. f) Lastly, the end-effectors release the two parts of the smoke detector into the designated bins on the worktable.

accomplish the disassembly task, the shape of the template, the shape of the custom-made tool, and the stiffness parameter of the VSGripper used as a vise were optimized. We performed the same task with various stiffness levels, yielding the following valuable insights:

- Insufficient stiffness can result in failure for two reasons: firstly, the device may not be well positioned when the vise closes and secondly, the device can exhibit excessive movements under external forces assuming unfavorable postures for the next steps. Usually an insufficient stiffness leads to the bending of the tool.

- Employing a traditional rigid vise leads to failure because it does not provide enough space for subsequent steps.

From the lessons learned, an optimal stiffness level of the soft vise was set to 0.8 on a scale from 0 to 1, where 1 represents the most rigid behavior of the VSGripper.

5 Conclusion

In this deliverable we present a hardware and software toolchain for the smoke detector disassembly process using reconfiguration and adaptation capabilities of the proposed recycling cell. **Video 1** shows an implementation where machine vision selects the appropriate disassembly operations, which are adapted based on vision results. The CNC milling machine is used to cut off the top of the smoke detector housing and expose the battery. **Video 2** shows an alternative solution based on variable stiffness gripper applying the levering operation. While the first approach requires additional machinery (CNC mill), it can be applied to more smoke detectors than the second approach. This is because not all our smoke detectors afford this second solution.

Our analysis has shown that it is quite difficult to open smoke detectors as they are generally designed not to be user-serviceable. Thus to facilitate the recycling of smoke detectors, the manufacturers of smoke detectors should redesign their products. More specifically, it would be beneficial if the batteries were designed to be removable, preferably with a spring-type base, instead of being soldered in place. This would enable an efficient separation of smoke detector components and streamline the recycling process.

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