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Towards Automated Disassembly for Battery Removal of Robot Vacuum Cleaners

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Abstract

The annual amount of electronic waste is increasing worldwide, and the number of battery-powered electrical appliances, such as Robot Vacuum Cleaners (RVCs), is also on the rise. The current state-of-the-art disposal process involves collection, partial disassembly, shredding, and subsequent sorting, which currently does not prioritize batteries, leading to fire incidents. Furthermore, this process does not guarantee that other value-preserving recycling methods can directly reuse materials as recyclate. Rather than having humans perform this dirty and hazardous task, robot-based disassembly could serve as a new and effective treatment to address these issues. This paper presents a case study of a critical step: the robot-based removal of batteries from RVCs. The proposed solution is a robust and modular robotic cell that fully automates the removal of spring terminal batteries from RVCs once a user feeds the object into the cell. The disassembly process consists of screw detection, unfastening, removal of the battery cover, and finally, removal of the battery. For this objective, we use a force-controlled skill-based robot programming framework combined with computer vision-based detection and comprehensive error handling strategies. Using the robot cell, we achieved an 81% success rate in the entire pipeline for different models.

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Keywords: Robotics; Circular Economy; Disassembly; E-Waste

1. Introduction

The growth in consumer electronics has been substantial in the last 10 years, resulting in an increase in electronic waste every year. According to the Global E-Waste Monitor 2024 [1], the volume of electronic waste has increased from 34 Mt in 2010 to a record 62 Mt in 2022. Furthermore, it has been projected to reach around 82 Mt by 2030.

In parallel, according to a report by the World Economic Forum [2], almost 40 % of household chores can be automated using robotics in the next decade. Tasks like cleaning the house, lawn mowing, dish washing, and cooking. This would dramatically increase the amount of electronic waste generated per household in the coming years. Specifically, considering RVCs, based on the trend observed by the International Federation of Robotics report 2024 and 2001, around 2.1 million RVCs were sold in 2023 [3] compared to just 5000 units in 2001 [4], a volume growth by a factor of 420.

Once these old devices are discarded, they are collected in material recycling facilities. Currently, the main method for handling such electronic waste is to first partially disassemble, often manually, then shred it, and finally sort the materials. For RVCs specifically, there is a huge risk of fire incidents occurring due to the lithium batteries present in each such appliance. Furthermore, these devices were subjected to varying degrees of wear, which also affects the batteries. Recent studies and news reports from all over the world have noted an increase in fire accidents due to lithium batteries in various stages of handling. Wang et al. [5] describe how fire accidents occur in non-application stages of a lithium battery. Therefore, there is an urgent need for solutions that address the problem of battery removal and disassembly of battery-powered appliances worldwide, which are: (a) automated, so no human intervention is required in this dirty and dangerous task, and (b) robust, to han-

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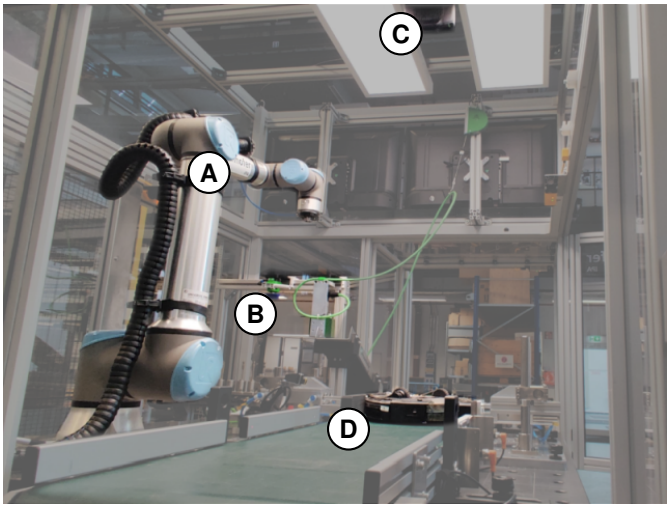


Fig. 1: Robot Cell with (A) UR10e robot, (B) Tool station, (C) Zivid camera, and (D) RVC clamped.

dle varying workpiece states and real-time problems during the disassembly operation.

In this paper, we provide a case study of an automated disassembly robot cell, shown in Fig. 1, that can address these challenges for RVC devices. The main contribution of this work can be summarized as follows.

1. An automated disassembly robot cell design to treat RVCs with (a) different End Of Life (EOL) conditions, (b) distinct model designs and (c) undefined feed-in poses.
2. A Behavior Tree-based disassembly task sequence that handles disassembly with comprehensive error handling and recovery capabilities that increase the success rate by 9 %.
3. Reliability study of the battery separation system with a performance of 81 % success rate on 27 samples with different EOL conditions spanning 15 different product designs (listed in Tab. 1).

2. Problem statement

We aim to remove batteries from typical RVCs, such as the *eufy* one seen in Fig. 2. These batteries are usually in a separate battery compartment (A) of varying shape, which is locked by screws (B) with different drive types of typically *pozidriv* and *phillips* styles with diameters of 2 mm to 4 mm and lengths of 4 mm to 30 mm (see [6]). These elements need to be removed before the battery is accessible. The accessibility and visibility of the compartment are often restricted by dirt, rust, or structures such as wheels or brushes (C). Within the compartment, batteries can be connected to the chassis via spring-loaded contacts or cables. Furthermore, batteries are delicate and should not be subjected to mechanical stress or heat.

3. Related work

Research in lithium-ion battery disassembly has been dominated by Electric Vehicles (EVs). Review articles like [7] and [8] provide an exhaustive list of how this problem is being thoroughly researched ever since EVs started becoming mainstream. However, there are many smaller devices, from household appliances to personal mobility solutions, that also need a safe way to dispose of their respective lithium-ion batteries during recycling. Some works like [9] and [10] provide information on the disassembly of RVCs and personal mobility devices, respectively. Specifically, the articles [6] and [11] give a good overview of the disassembly potential of RVCs by robotic automation. With reference to these articles, our contribution describes a robot cell that is capable of doing this. Articles [12] and [13] describe a framework and a task planner, respectively, for the disassembly of lithium batteries from EVs. Our robot cell will focus on household devices through a combination of task planning and error handling approaches.

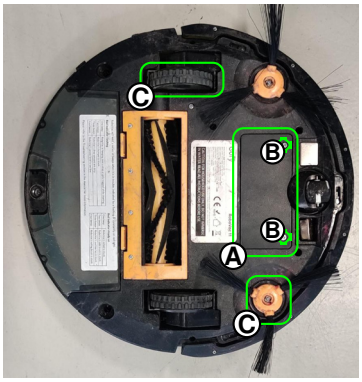


Fig. 2: RVC with (A) Battery Compartment with (B) Screws, and (C) Motors.

4. Methods and Materials

In this section, an overview of the hardware, software, and system design incorporated in this disassembly project is given.

4.1. Robot Cell Setup

The experimental setup consists of a robotic cell with a Universal Robot UR10e[1], a Zivid camera[2] for object detection, a GRIP based tool changing station[3] for a screwdriver and a vacuum gripper, a pneumatic gripper to remove or separate the screw from the screwdriver bit after unfastening operation, and a conveyor belt for loading and unloading operations of a RVC unit. Fig. 3 describes the architecture of the system.

4.2. Software Components

In this work, the following software systems were used to run the disassembly application:

1. *ROS Noetic*: To combine different hardware and software frameworks, we utilize Robot Operating System (ROS), which provides low-level drivers and communication between different components.
2. *pitasc Robot Programming Framework*: To control the robot, we utilize a Fraunhofer IPA software framework, *pitasc*[4], which is an extension of the instantaneous Task Specification using Constraints (iTaSC) system developed by Schmits et al. [14], which is capable of gen-

[1] www.universal-robots.com/products/ur10e
[2] https://www.zivid.com/zivid-2-plus
[3] www.grip-gmbh.com/en/grip_products/ac063
[4] www.pitasc.fraunhofer.de

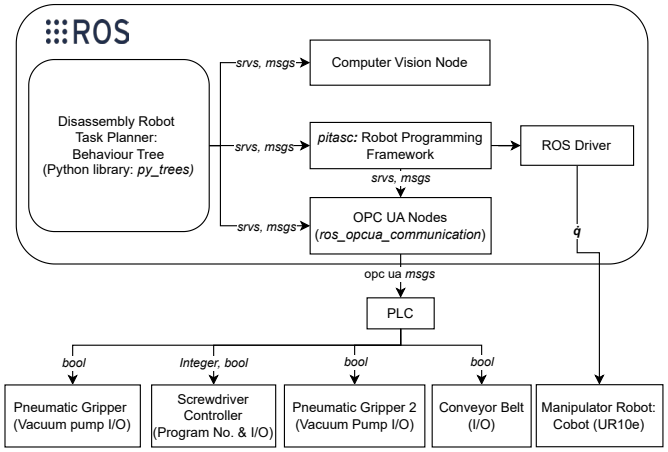


Fig. 3: The developed system architecture. Here, "srvs, msgs" denote ROS services and messages, "$\dot{q}$" joint velocities and "opc ua msgs" OPC UA messages.

erating robot motions by specifying constraints in the geometric, dynamic, or sensor space between the robot and the environment. *pitasc*, introduced by Naegele et al. [15], provides a modular skill system that allows, among others, to incorporate Force-Torque-Sensors (FTSs) to provide task-level force control and control of the robot at the joint velocity level. It also has the possibility to incorporate other peripherals, such as a screwdriver, via OPC UA/ROS, and uses a hierarchical state machine for process control.

3. *Behavior Tree for Task Sequence*: The disassembly system in our robot cell was built using Behavior Trees, the modular and hierarchical framework used primarily in robotics, game AI, and autonomous systems to model complex decision-making and behavior execution [16] to combine all peripheral devices described in this paper. The specific description of the built tree is explained in Section 4.3.
4. *Object Detection*: For screw localization, battery cover, and battery detection, a Zivid camera was mounted on top of the robot cell. The 6D poses of specific objects were provided through a custom ROS message upon service call from the behavior tree to facilitate disassembly operations within the designated task nodes.
5. *OPC UA*: The peripheral components and tools, including a screwdriver, conveyor belt, and product fixation system, are controlled by program logic control (PLC). The connection between the ROS environment and PLC is established using the OPC UA through the ROS driver `ros_opcua_communication`[5]. This control architecture is designed to offer flexibility, enabling the integration of additional tools and components into ROS without requiring component-specific drivers.
6. *ROS Drivers*: The manipulator arm motion, provided by the *pitasc* framework, is performed by using the ros driver `Universal_Robot_ROS_Driver`[6].

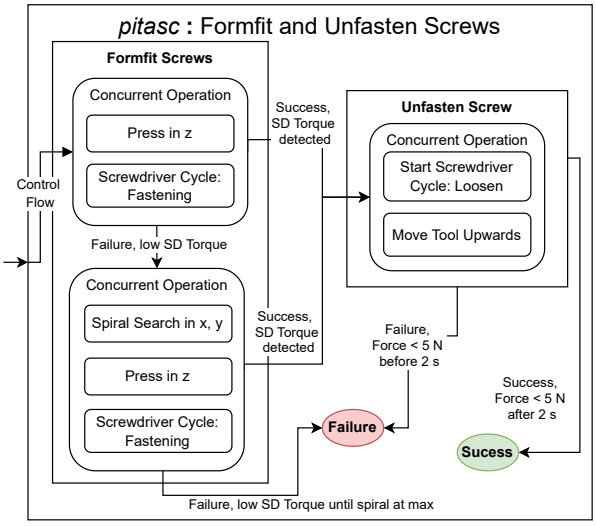


Fig. 4: Screwfit system. Here, SD denotes Screwdriver.

4.3. System Description

This section describes in detail the working principle of our robot cell.

4.3.1. Disassembly Task Planning Behavior Tree

The complete disassembly pipeline is handled by a Behavior Tree-based task planning sequence. This sequence extensively defines multiple error-handling approaches to fully automate the task once the user places an RVC through the input door of the robot cell and presses a button. Fig. 5 shows the tree-based flow diagram. This task sequence was created according to the steps taken by a human while manually disassembling an RVC in a non-destructive way. We utilized the Python library `py_trees`[7] for the entire pipeline, where each child node handles individual steps with recovery or error handling plans. On a high level, the system consists mainly of five operations, which are:

1. Workpiece feed-in, detection, and clamping.
2. Screw Detection, unfastening, removal, and verification.
3. Battery cover detection, removal, and verification.
4. Battery detection, removal, and verification.
5. Workpiece feed-out.

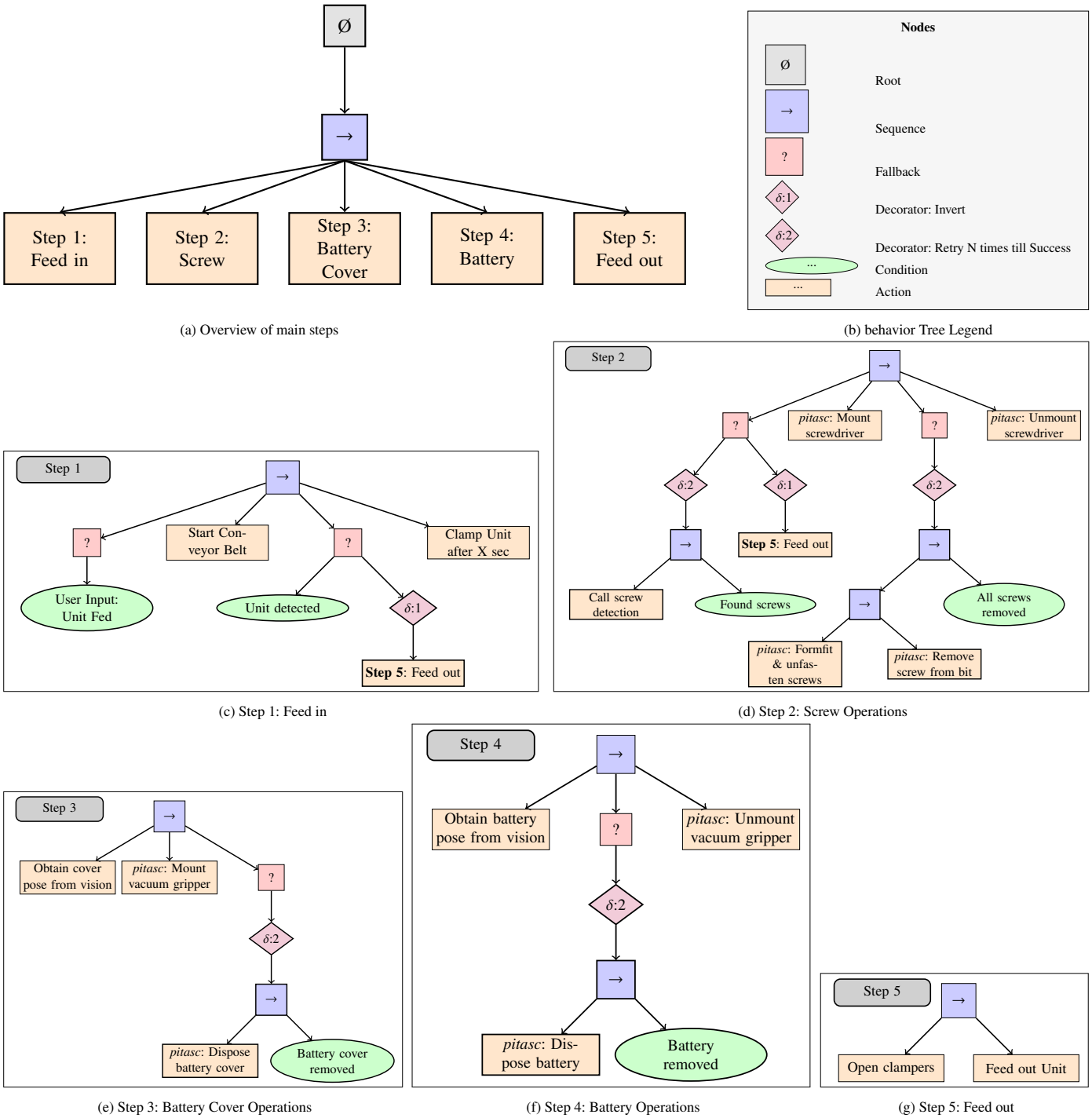
The demonstration of successful disassembly is provided in the supplementary video[8].

4.3.2. Error Scenarios and Ways to Tackle

As a result of the unknown condition of the RVC, the robot cell needs to be able to handle different errors. Therefore, we established an in-depth error handling system that is able to automatically handle the RVCs without human intervention. Described below is a non-exhaustive list of errors we faced during the disassembly process and how we tackled them:

Failure to detect the unit on the conveyor belt due to reflective surfaces on the RVCs. The laser sensor on the conveyor belt sometimes receives irregular signals, thus failing to recog-

[5] https://github.com/iirob/ros_opcua_communication
[6] https://github.com/UniversalRobots
[7] https://py-trees.readthedocs.io
[8] https://www.youtube.com/watch?v=hrnt9gLvo60



(a) Overview of main steps

(b) behavior Tree Legend

(c) Step 1: Feed in

(d) Step 2: Screw Operations

(e) Step 3: Battery Cover Operations

(f) Step 4: Battery Operations

(g) Step 5: Feed out

Fig. 5: Robot Disassembly Task Sequence - Behavior Tree

nize the RVC dimensions and not providing a time estimate to stop the conveyor belt for clamping operation. In this situation, the fallback state is to move the belt for a short time to feed the RVC out and reset the pipeline.

Failure to identify screws on the RVC happens when the vision node fails to identify the screwheads on the workpiece due to their different EOL conditions. The fallback state is to retry N times and, if it still fails, to let the unit feed out.

Failure in the screwdriver formfit occurs in some instances because the screwhead does not have the appropriate conditions to mechanically fit the screwdriver bit. This specific case was handled in our *pitasc* system based on its native state machine architecture shown in Fig. 4.

False positives in the screw removal task occur when the robot program considered successful screw removal from the RVC and continued to drop screws into a collection bag, but in reality, the screw would still be on the RVCs. The fallback step contains a confirmation step using the vision node that compares the state before and after the operation and performs

screw unfastening in case of failure. This fallback runs N times until success or directly feeds the workpiece out of the cell.

False positives in the battery cover removal task is similar to the screw removal failure. So, the fallback of this step is also reconfirming the status and removal for N times until success or feed out of workpiece in the event of failure after N iterations.

False positives in the battery removal task is another situation similar to screw removal failure. Thus, just like the previous two, there is a fallback of N tries of vision-based confirmation and removal till success, or directly feeds out of the workpiece in case of failure still.

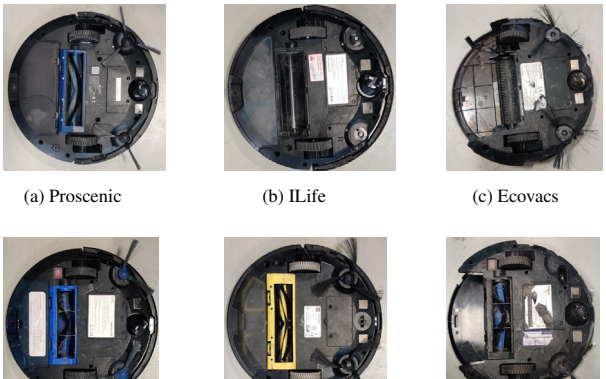
5. Evaluation Setup

To evaluate how robust and reliable our solution is, we follow a qualitative and quantitative study of the performance of our complete process on RVCs for the disassembly.

5.1. Workpiece categories

We collected multiple discarded RVCs from recycling facilities for our case study. These units were distributed across 6–8 companies with varying EOL conditions and design variations (shown in Fig. 6). The EOL conditions of different RVCs were (a) dirty with mud, human hair, and pet fur, (b) broken or discolored plastic parts of the chassis, and (c) removed or damaged sticker labels on the battery cover. The design variations can be summarized into mainly three categories:

1. Category 1: RVCs with direct access to the lithium battery compartments on the bottom chassis, requiring only 3 operations to separate the battery: (a) 2-3 screw removal, (b) removal of covers with different designs, and (c) battery removal.
2. Category 2: RVCs that require complete removal of the bottom chassis to access the battery compartment. Although requiring relatively less manipulation, these units demand sophisticated handling: (a) multiple screw removal, (b) complete chassis detachment with multiple sub-tasks, and (c) battery removal.
3. Category 3: RVCs with batteries deep inside the chassis, therefore, requiring extensive multi-sided operations and complex manipulations.



(a) Proscenic (b) ILife (c) Ecovacs

(d) Eufy (e) EASY HOME (f) Bagotte

Fig. 6: Variants of RVCs used in this study (Category 1).

5.2. Performance Analysis

The goal is to achieve disassembly for all categories of RVCs. However, in the initial phase, only category 1 RVCs have been taken into account and a feasibility study on safe battery removal was conducted, which could potentially help recycling facilities avoid fire incidents caused by batteries mixed in electronic waste piles. The system was evaluated on 27 different RVCs out of which 22 followed the entire pipeline, but 5 failed for various reasons, shown in Tab. 1. Each step performed is categorized into three outcomes: (✓) for successful, (**F**) for failed, or (**-**) if not performed at all. Taking into account the safety concerns during the initial phase, real lithium batteries were replaced by 3D printed replicas of similar dimensions and weight to demonstrate robot performance on batteries with ideal conditions (no deformation from perforations or punctures). Furthermore, these battery dummies were designed according to the spring-terminal connector (found in some models) rather than a typical wired plug connector, which reduced the system complexity of the initial prototype being developed. Currently, the robot cell is being modified into a dual robot-based setup with the inclusion of an Igus Rebel[9] robot arm with pneumatic pliers to operate on batteries with cable connections.

6. Results and Discussion

As shown in Tab. 1, different model designs were used to check the reliability of the disassembly cell through an evaluation that contained two different methodologies.

6.1. Success Rate of Complete Process

Firstly, the system's ability to execute the complete pipeline was observed, from RVC feed to battery separation. Of the total of 27 units tested, each with different brands and EOL conditions, 22 units successfully completed the entire pipeline, providing a complete pipeline success rate of 81 %. This result demonstrates the robustness of the robot cell to a wide range of model designs. Meanwhile, the other five models are shown in Tab. 1. The complete battery removal process took about 4.5 min from feed-in to feed-out of the RVC unit.

6.2. Success Rate of Individual Steps

Secondly, we analyze the performance of each step in various models. We observed that one of the most unreliable steps in the complete pipeline is the screw-unfastening operation. Here, based on how strong the EOL conditions are, we would observe (a) false positive or false negative detections from the vision node, (b) unsuccessful formfit due to screw heads being rusted, or (c) failure in screw removal due to damaged threadings. The cause of this unreliability can be attributed to various screwhead sizes, wear and tear, and diverse thread lengths. To address this issue, we introduce an additional logic system based on a state machine as shown in Fig. 4, which allowed us to achieve reliable unscrew operation. We also observed a failure in battery cover detection due to the dirty state of one unit, shown in Fig. 6f, which we did not address in this work and which is left for future work.

[9] https://igusrebel.com

Table 1: Performance of Robot Cell on Category 1 RVCs (with only the five failed units; 22 units went through successfully).

Steps	Workpiece			Screws				Battery Cover			Battery			Workpiece
Substeps	Feed-In	Detect	Clamp	Detect	Unfasten	Remove	Verify	Detect	Remove	Verify	Detect	Remove	Verify	Feed-out
Bagotte BG600	✓	✓	✓	✓	**F**	-	-	-	-	-	-	-	-	-
Bagotte BG800	✓	✓	✓	✓	✓	✓	✓	**F**	-	-	-	-	-	-
eufy G10 Hybrid	✓	✓	✓	✓	**F**	-	-	-	-	-	-	-	-	-
eufy RoboVac G10 Hybrid	✓	✓	✓	✓	✓	**F**	-	-	-	-	-	-	-	-
Proscenic Cocosmart 820T	✓	✓	✓	✓	**F**	-	-	-	-	-	-	-	-	-

7. Conclusion and Outlook

In the current stage, this cell can provide a robust system for initial disassembly and battery removal that addresses the fire hazard in recycling facilities. By incorporating this robot cell as an initial step, fire events caused by accidental shredding or mishandling of batteries can be avoided. In addition, the exposure of workers to batteries in dangerous states can be limited. In future versions, ideas such as the sandbox system of [17] could be explored to handle fires during disassembly operations inside the robot cell. However, certain assumptions and limitations followed during development need further work.

7.1. Limitations

The robot cell is currently limited to handling specifically RVCs. The system needs them in a specific orientation and also assumes that all screws are in good condition to ensure successful form-fit and unfastening. Fire safety measures, such as extinguishers, are not integrated into the design. Furthermore, the battery replicas only simulate ideal battery conditions (i.e., no deformation by perforation or punctures), which is a limitation of our approach. All battery connections are assumed to use spring terminals rather than plug-in cables, allowing simple pick-and-place removal with vacuum cups. Additionally, the disassembly behavior tree is not suitable for a wider category of electronic devices and requires an update to be deployed for the disassembly of other products.

7.2. Future Works

Currently, we are testing multiple additional modules and modifications to make our disassembly robot system suitable for a wide range of electronic devices like RVCs, personal laptops, and robot lawnmowers. Some of them are: a screwdriver bit change station to handle different screw drive designs on the workpieces based on image-based categorization, a dual robot setup to handle operations such as battery cable cutting and PCB cable cutting, and additional tool designs for handling category 2 RVCs described earlier.

Acknowledgements

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