

57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024)

Towards Circular Economy: Process Description, Requirements, and Data Set for Robot-based Disassembly of Small Electrical Appliances

Anwar Al Assadi^a, Lasse Höltge^a, Max Brower-Rabinowitsch^a, Frank Nägele^a, Werner Kraus^a,
Marco F. Huber^{a,b}

^aFraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart

^bUniversity of Stuttgart, Institute of Industrial Manufacturing and Management IFF, Chair Cognitive Production Systems, Allmandring 35, 70569 Stuttgart

*Anwar Al Assadi, E-mail address: anwar.alassadi@ipa.fraunhofer.de

Abstract

European countries generate approximately 4.7 million tons of electrical waste annually. The generated electrical waste includes an increasing number of battery-operated electrical devices such as robotic vacuum cleaners, which contain valuable components like electrical motors and battery systems. However, environmental and economic concerns require alternative treatment strategies besides shredding and sorting, which is the current state-of-the-art technology. Robot-based disassembly might be an alternative strategy to gain valuable and possibly reusable components. The requirements of the disassembly processes must be given to design novel robot-based solutions and identify relevant future research areas. For this, a quantitative examination of end-of-life (EOL) robot vacuum cleaners is carried out to collect the expected handling and disassembly steps, including the product state. Accompanying this paper, an open-source data set with 37 manual and complete disassembly experiments from 21 RVC manufacturers (incl. 1.113 images) for scientific and industrial usage is published. Therefore, the required disassembly processes, expected states, joining technologies, robot dimension, battery capacity, and partial functional test results are provided. On this basis, disassembly processes, challenges, and requirements for a robot-based solution are identified and a cell layout is proposed. This procedure can be applied to the disassembly of other unknown EOL products.

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Peer-review under responsibility of the scientific committee of the 57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024)

Keywords: Disassembly; Circular economy; Robotics; Robot vacuum cleaners,

1. Introduction

According to the E-Waste Monitor of the United Nations Institute for Training and Research (UNITAR), 53.6 million tons of electric waste were generated in 2019. The number is expected to grow to 74.7 million tons by 2030 [11]. Especially, emerging products such as robotic vacuum cleaners (RVCs) or robotic lawn mowers (RLMs) contain valuable components like sensors, batteries, and electric motors [24]. Multiple options exist for recycling a product at the end of its operational life. Specifically, mechanical shredding and separation, is a standard recycling option for electrical appliances. This has a harmful direct and indirect impact on the environment. In addition, electrical waste is frequently related to illegal trade, improper treatment, and greenhouse gas emission [11, 19].

A more economical option is remanufacturing. This process describes resetting a used product to the original performance specifications [18]. Sub-processes of remanufacturing are disassembly, cleaning, inspection, repairing, reassembly, and testing [21]. A case study of [9] showed the positive economic potential of remanufacturing of RLMs. A centralized remanufacturing by an OEM in combination with a spare parts warehouse is a prerequisite for this. However, labor costs and the high variety of products are challenging in implementing remanufacturing or circular economy businesses [25, 14]. Robot-based / automated remanufacturing and disassembly is considered a key enabler for circular economy [26, 3, 13, 22].

For this, the technical requirements (e.g., which joining technologies occur, what the basic product properties are, what the challenges for automation are, and how the design of a robotic solution looks) for implementation still need to be addressed. These requirements are derivable from a semi-quantitative fieldwork examination of EoL appliances. Fundamentally, the

* Corresponding author; anwar.alassadi@ipa.fraunhofer.de

technical conditions have to be proven that components are suitable for circular economy or remanufacturing.

The rest of this paper is organized as follows: section 2 gives a brief overview of related works. Section 3 introduces the procedure of the manual disassembly and the following steps. Section 4 presents the results of this work. Section 5 discusses the results. Section 6 gives a short summary as well as an outlook on the discussed topics.

2. Related Work

Recent and previous studies that dealt with automated disassembly focus on batteries from electric vehicles or electric motors [6, 12, 7, 20]. Past works like [27, 23, 8] took household appliances (TV, washing machine, laptop) into account. However, these products differ due to the size and installed components, which have changed over the years. The mentioned works also focused on one joining technology or process module, e.g., unfastening or localization.

Recently [24] described the rough product characteristic (e.g., material composition and partially geometric properties) by using 10 RVCs. Another aspect of this work was the assessment of the recycling chain by using 125 RVCs to determine the composition of the material stream. However, details (e.g. joining distribution, disassembly steps and EoL states) are missing to design and implement an robot-based disassembly cell. Practical challenges in robot-based disassembly of electronic devices are discussed in [10].

There needs to be more knowledge about the state of EoL of small electrical appliances. This study addresses the need for more requirements regarding the product properties and states of electrical battery-operated appliances by using RVCs as examples. Systematical disassembly, documentation, measuring, and testing are conducted to collect the requirements for the further design of a robotic solution.

3. Methods and Materials

In this section, an overview of the samples and the procedure of manual disassembly is described. The typical E-waste flow in Germany is given in Fig. 1. The considered RVCs of this work have been provided by the municipal collection, where the selection has been conducted without intentionally order or schema. Tab. 2 summarizes the sample overview of the disassembled devices. RVC A, which is a Roomba from iRobot, is one of the most manufactured robots in the world [28]. The manual disassembly has been tried as much as possible as semi-/non-destructive disassembly. In the next step, we documented the disassembly steps similar to Al Assadi et al.. However, we extended the schema by adding product and screw properties: screw drive type, screw size, screw length, and battery capacity. Tab. 1 gives the documented joining technologies. The documented disassembly is analyzed automatically by using a python script to derive the basic properties of the RVCs and the associated requirements of an automated solution.

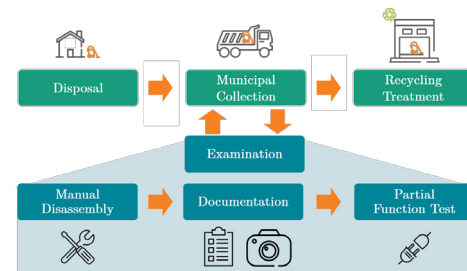


Fig. 1: The main German process flow of E-waste treatment (in green) [5], including the bypass of this work (in blue).

Testing components is essential to justify the potentially high effort to realize an automated robot-based disassembly. This testing indicates whether the components can be reused in the context of remanufacturing or not. The effort of testing printed circuit boards, batteries, or sensors is much higher than the principle simplified testing of motors (rotating or not). For this reason, the principle motor testing has been conducted. This testing was conducted using a laboratory power supply. Device manuals were screened to estimate the operating voltage and current. However, it was only sometimes possible to find this physical quantity in the manuals of the original manufacturer. For this reason, we test step-wise the voltages of 3 V, 6 V, 9 V, and partially 12 V. The current has been kept constant at 0.5 A.

4. Results

This section that follows presents the results of this work.

4.1. Basic properties

All disassembled RVCs belong to the German electric disposal group 5, which includes all electrical appliances with edge length up to 50 cm and a display smaller than 100 cm². Fig. 2 shows the general structure and lists the basic properties of the considered RVCs. These basic properties are essential to designing an adequate robot cell. Exemplary the weight of the RVCs, which is at most 4632 g. In combination with the disassembly tool/step (e.g., parallel electric gripper 250 g, tool changer 300 g) the weight of the RVCs, and safety factor of 1.5 serves as an indicator for an initial estimate of the required robot payload (7773 g). The battery capacity should be considered in risk assessment and evacuation scenario/system.

4.2. Structure and disassembly steps

The occurrence of joining techniques is documented and analyzed to design and provide the appropriate tools. Fig. 3 gives an overview of occurring joining techniques. Fig. 3 shows that the unfastening of screws would make up a large part of the (automated) disassembly of these devices. This becomes clear in an exemplary disassembly, which can be found in Tab. 3. The general structure of an RVC is illustrated in Fig. 2. The two parts are mostly connected electrically and mechanically.

Table 1: The documented joining technologies and their description.

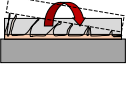
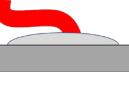
Joining	Description	Schematic
Screw	Force-locking. Screw connection of two parts. Mostly plastic parts with metal screw (self-forming).	
Cable	Denotes a cable plug connection. Release by tensile force. Additional snap connection for tension lock also possible.	
Loose	No restriction of the degrees of freedom of movement.	
Snap	Form-fit. Fixed connection made of plastic, is made by snapping (here always detachable, partial destruction due to lack of access). Only snap-fit hooks occur. Elastic deformation of a joining part and subsequent hooking	
Plug-In	Special case of the loose connection. Movement is restricted to one degree of freedom.	
Clamp	Force-locking due to a tight fit. Can be moved with force in one dimension.	
Adhesive	Materially bonded components. Connection can be released with force by peeling stress.	
Solder	Materially bonded components (typically contacting and cable end) by using soldering material. The soldering material is melted and placed over the materials to be joined.	

Table 2: The sample overview of RVCs.

RVC	Quantity per producer
A	9
B,C	3
D,E,F,G	2
H,I,J,K,L,M,N,O,P,Q,R,S,T	1
20 manufacturers	36 devices

Images are taken between the disassembly steps, accessible at [4].

4.3. Partial functional test

Partial functional test is conducted to check the potential of remanufacturing and reuse. 128 out of 141 motors (90.8 %) of the RVCs tested rotated during the principle function test. The statistics show great potential for these motors to be subjected

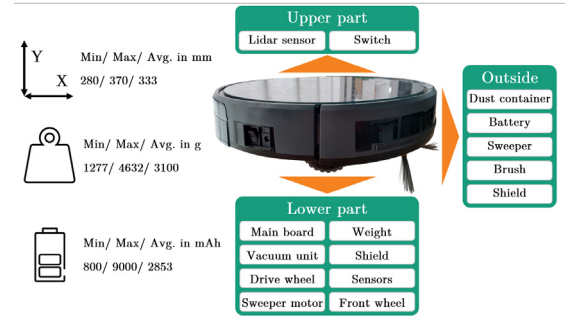


Fig. 2: Exemplary RVC structure.

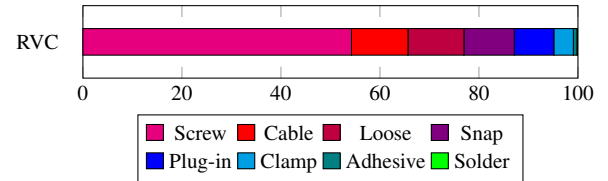


Fig. 3: Distribution of joining techniques in %.

Table 3: Exemplary disassembly sequence of a RVC including joining techniques (JT).

Step	Part	JT	Challenges for disassembly
1	Dust container	Snap	Joining not always visible
2	Battery cover	Screw	Black screws, back cover
3	Battery	Cable	Variation of plugs, incl. small gripping surface
4	Brush (1&2)	Clamp	Rotating component
5	Sweeper cover	Screw	Tiny screws, limited access
6	Sweeper	Loose	Rotating component
7	Shield cover	Screw	Tiny screws
8	Shield	Cable	Fixed with cable ties
9	Upper part housing 1	Screw	Counterbore screws
10	Lower part housing 2	Cable	Connection to housing 1
11	Main board	Cable	Accessibility of plugs (vertical & horizontal)
12	Main board	Screw	Vertical & horizontal mounting of plugs
13	Vacuum unit	Screw	Dusty
14	Sweeper motor	Screw	Accessibility
15	Drive wheel unit (1&2)	Screw	Hidden spring
16	Brush motor (1&2)	Screw	-
17	Weight	Screw	-
18	Shield bracket	Screw	-
19	Sensor 1	Snap	Two tools/ hands are required, force have to applied
20	Sensor 2	Screw	Tiny
21	Front wheel	Snap	Rotating component
22	Power switch	Plug-in	Accessibility
23	(Lidar sensor)	Screw	-
24	(Glass cover housing 1)	Adhesive	Handling & Visibility

to a more thorough functional test and thus be suitable for the spare parts market as used parts.

4.4. Analysis of screw connections

Due to the significant number of screw disassembly steps, this subsection is focusing on screws. 51 screws are used on average per RVC in our considered samples. Tab. 4 shows the

Table 4: Occurrence of the screw drives in %.

Screw drive type	Size	RVC Value
Cross recess	PZ01	97.22 %
Cross recess	PZ00	69.44 %
Internal hexagonal	2	5.56 %
Torx	TX9	5.56 %
Torx	TX10	2.78 %
Torx	TX20	2.78 %
Triangle	1	2.78 %

probability of occurrence of the screw drive types over all considered RVCs. The value is to be interpreted as meaning that there is a 97.22% probability that a screw with drive Cross recess is occurs in the RVC under consideration. The number expresses the proportion of screw heads within an RVC. This is particularly important with regard to the design of the bit changer, as the mere presence of a drive means that a bit must be kept available for it in the event of disassembly. The statistics confirm the dominance of cross recesses (Pozidriv) in electronic devices, which has also been seen in the use-cases of previous works like [23] or [8]. On this basis, a bit for this screw drive has to be kept in storage in an automated approach.

The screws used vary in length from 4 mm to 30 mm (cf. Fig. 4). Various approaches can be used to remove the screws after the disassembly. Examples include suction, stripping or vacuum-assisted removal, however the suction based approach is influenced mainly by the length of the screws. The minimum bending radius of the suction nozzle depends on the length of the screw to prevent blockage.

4.5. General challenges and suggested improvements

RVCs typically comprise two shells. Electrical components are built in both shells, which requires cable/wire routing from one to the other shell. That requires reorientation and reposi-

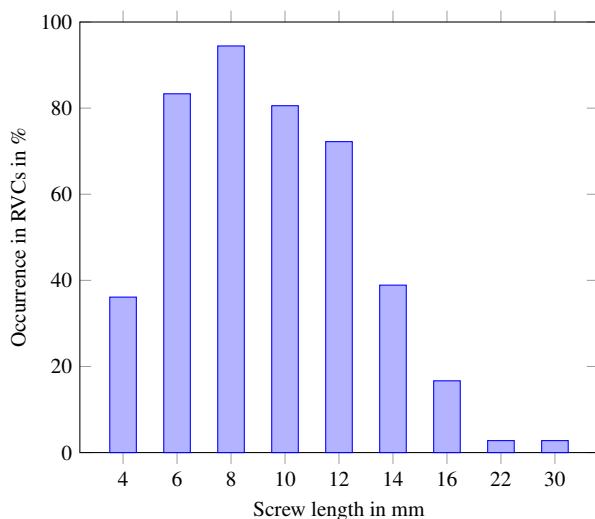


Fig. 4: The occurrence of screws in relation to the screw's length.

tioning of the product while (automated) disassembling. In the context of cables and wires, the connectors are hardly spatially accessible. Sensitive gripping skills are required in case of non-destructive disassembly. Mostly the two shells of RVCs are assembled with several screws, which are in counterbores. An example is given in Fig. 5a. The counterbores are relatively deep, which makes the screw drives invisible—combined with often black shells, computer vision systems have to provide lighting and other methods to detect the proper screw drive. One positive aspect is the accessibility of the battery systems, which allows them to be removed from the outside of the housing without opening the two shells. An example is shown in Fig 5b. Only two screws had to be loosened for this. The motor and wheels are primarily designed as one unit in the case of RVCs, which makes replacement easier. However, this unit is accessible in most cases by opening the two shells.

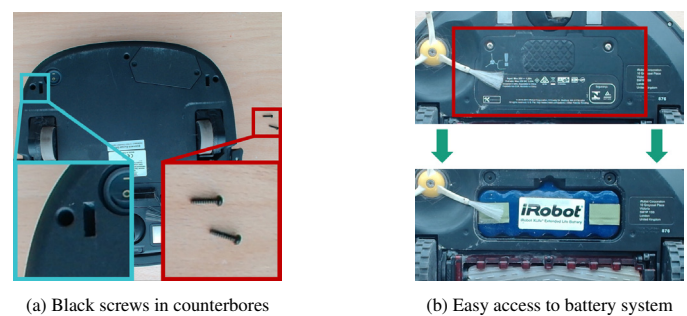


Fig. 5: Practical gained knowledge about the disassembled devices.

4.6. Outlook on newer RVC designs

Due to the time delay between the market supply and the recycling flow, a newly manufactured RVC was disassembled to determine the differences and similarities. As can be seen in Fig. 6, the (depth) counterbores challenge (up to 39 mm) is also present. After lighting the counterbores, it is possible to detect the screw head and screw drive. Regarding features, several manufacturers have extended their products by wiping cloth, self-cleaning stations, or LIDAR sensors for navigation. The considered device is equipped with more built-in sensors compared to EoL models. Therefore, an increased amount of cables have been found inside. The cable fixation with barbed hooks as well as the obscuring of screws by a bundle of cables, pose challenges for an automatic disassembly process.

4.7. Battery removal in detail

Due to the legal, economic and automation potential of battery removal, a deeper analysis of the process is carried out. As described in Tab. 3 the removal of a battery system is usually possible without disassembling the entire RVC. Some examples can be found in Tab. 5. The general procedure is described as: unfastening screws, handling of a cover and battery removal (including unplugging). The handling of covers has to consider disassembly motions like slide, pull, lift or twist according to the disassembly motion definition of [29]. Most of the covers

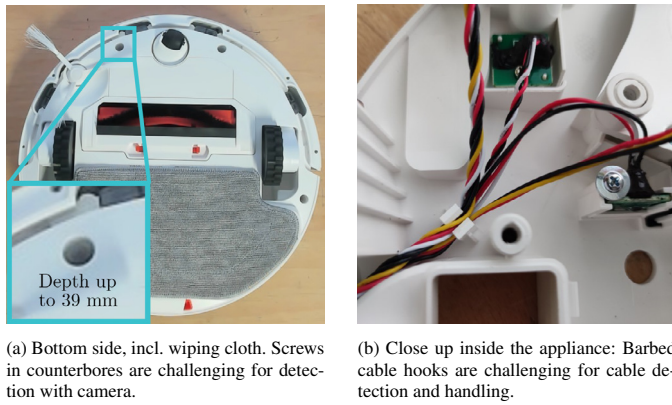


Fig. 6: Exemplary composition and challenges of new RVC.

have two lugs, which require twist and / or slide and pull motions.

Table 5: The removal of a battery system, exemplary for four different RVCs.

RVC	Unfastening screw	Cover handling	Battery removal
A			
B			
D			
H			

4.8. Designed robot cell

Based on the gained product information, a robot-based disassembly cell is designed. Fig. 7 shows the derived process technologies, which are a robot system, a tool-changing system, grippers (parallel and suction), an automatic screwdriver, a computer vision system, and a flexible fixation system. The tool-changing system is required due to the variance of tasks (handling and unfastening) that must be executed during the disassembly. The component's contours are non-uniform and vary, requiring handling flexibility. Two gripping principles are therefore considered (vacuum and parallel grippers). The vacuum gripper would be predestined to remove the device's battery systems. The compartments of battery systems have hardly any gripping surfaces for a parallel gripper; a vacuum gripper could be suitable here. In the case of non-destructive disassembly, an automatic screwdriver is proposed since almost all parts are connected by screws. Most RVCs have a circular base. However, other electrical appliances like RLMs have a non-circular base. This requires a flexible clamping concept when the cell disassembles different product classes.

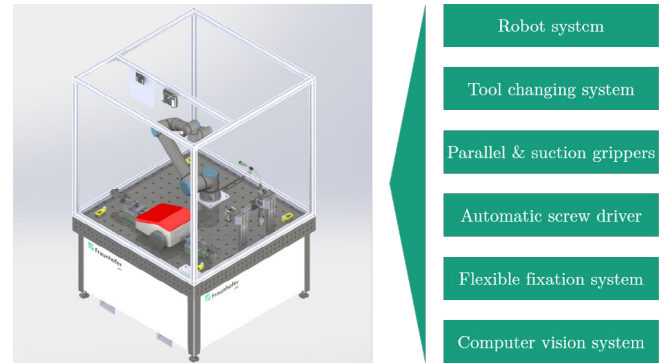


Fig. 7: The designed robot-based disassembly cell.

5. Discussion

The data collected through this work is a brief view of the e-waste stream of RVCs. The electronic consumer market is very dynamic. Therefore, data must be collected periodically to ensure that future product designs and products are considered in automated-based disassembly approaches. Another source of information for the rough design of automated disassembly solutions is websites of the do-it-yourself (DIY) community like iFixit [17]. The drawback of this approach would be the EoL state of the products, which needs to be represented there. On the other hand, there are efforts to introduce a digital product passport on the European market. Information on disassembly could be beneficial here.

6. Conclusion and Outlook

The main conclusion that can be drawn is that automated disassembly will be challenging based on the gained practical knowledge. In some cases, a combination of automated and manual disassembly is proposed. Design for (automated) disassembly is strongly recommended to reduce the effort for automated solutions. Besides design for (automated) disassembly, active disassembly could be properly helpful regarding some snap fits [1].

Based on the principle function testing, sub-components' potential for reuse, remanufacturing, or refurbishing has been confirmed. Further investigations should also take into account the aging condition of the motors. Screw connections, especially cross recesses, are a widely used joining technology in the product design of the considered electrical devices and should be crucially regarded. From the perspective of other electrical appliances, our presented results could be combined with [15] and [16] to develop a cross-product assessment of disassembly. Our future work will consider other emerging products such as RLMs, where also motors and battery system are essential for remanufacturing and recycling, see App. A.8. The development of individual process technologies such as machine learning-based localization, unfastening screws, cover handling, and other processes are pending. The proposed robot cell will be set up in a scientific facility. The aim is to validate

the proposed robot cell design in terms of the technical requirements and the economic aspects.

Acknowledgements

We like to thank Karle Recycling and Abfallverwertungsgesellschaft des Landkreises Ludwigsburg for their support in providing us the necessary RVCs and RLMs. The authors also acknowledge the financial support by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) within the project “Desire4Electronics” under grant number 67KI31054A.

Appendix A. Appendix

Another emerging product group are RLMs, due to their battery system and motors. The mounting direction of PCBs in RLMs could be considered as challenging due to the vertical and limited geometric accessibility. Another aspect are the connectors, which have to be detected and disassembled from the upper side. The motors of the RLMs can be dismantled with little effort. However, it should be noted that a nut is usually used to fasten the wheels to the motor, see Fig. A.8.

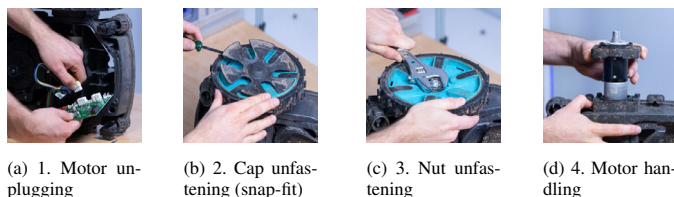


Fig. A.8: The disassembly of a RLM wheel motor.

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