Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 105 (2022) 273–277

www.elsevier.com/locate/procedia

29th CIRP Life Cycle Engineering Conference

Design of a robotic system for battery dismantling from tablets

Chuangchuang Zhou[a,b,*], Bart Engelen[a], Isiah Zaplana[a], Jef Peeters[a]

[a]*KU Leuven, Department of Mechanicla Engineering, Celestijnenlaan 300, 3001 Leuven, Belgium*
[b]*KU Leuven, PSI-EAVISE, Jan Pieter de Nayerlaan 5, 2860 Sint-Katelijne-Waver, Belgium*

* Corresponding author. Tel.: +49-152-0318-5386. *E-mail address:* chuangchuang.zhou@kuleuven.be

Abstract

Due to the rapid increase in sales of mobile electronic devices, the number of batteries ending up in waste electric and electronic equipment (WEEE) is also rapidly increasing. According to the EU legislation, all batteries need to be removed from WEEE, which is currently done manually for tablets, posing potential safety risks for workers and resulting in high processing costs due to the labour intensity of the required dismantling operations. Therefore, a robotic dismantling system is developed in this research to automatically remove both the back covers and batteries from a mixed waste stream of tablets of different models and brands. At the outset of the design process, a total of 47 randomly collected tablets were analyzed to define the location of the battery and the required manual dismantling time. Thereafter, a robotic bending method was tested for removing the back cover. Once the battery is exposed, two different methods are tested: using a heat gun to loosen the glue that fixes the battery to the rest of the tablet and a robotic scraping method with a spatula to mechanically extract the battery. Whereas the required time for only the heating showed to be more than 120s, the results with the bending and scraping tool show that the proposed robotic dismantling system is capable of removing the back cover and battery for 63% of the tested tablets in less than 90s. However, to increase the economic viability and robustness of the proposed method to be able to cope with the high variety in tablet model designs, future work is required to develop algorithms to recognize product models to enable to define and retrieve product specific toolpaths for dismantling.

Keywords: robotic dismantling; battery removal; tablets; WEEE

1. Introduction

With the rapidly increasing amount of WEEE that contains a battery , the proper collection and recycling of batteries from these devices is of increasing importance, as batteries contain a substantial amount of hazardous substances, which risk to pollute the environment and to pose a threat to human health if not properly treated when they reach their end-of-life. In addition, when they are not systematically removed from WEEE, there is a risk for fire incidents [1]. At the same time, the recycling of batteries form WEEE also encompasses substantial opportunities, as they contain also many critical and valuable metals, which can be reused and recycled to lower the impact of virgin material production. Because of this reason, the EU requires the removal of batteries from WEEE [2].
Nowadays, batteries in WEEE are mostly removed manually by the virtue of the high complexity and variety of electronic devices. This manual disassembly process is costly due to high labor costs and involves safety issues [3]. In addition, it is worth noting that, in the process of removing the battery, in some cases the battery is punctured, which is expected to also result in the release of toxic gases, such as fluoride, posing a threat to the health of the workers. Moreover, in some pessimist scenarios, many small electronic devices are directly shredded into small pieces for recycling without removal of the batteries, which poses risks of fire and explosion [4]. To cope with the increasing volume of batteries in WEEE as well as to

10.1016/j.procir.2022.02.045

overcome these safety issues and reduce the WEEE treatment cost, the development of an automated battery dismantling process is essential.

To date, a number of studies have explored automated dismantling strategies for similar products. For example, for the automatic disassembling of LCD TVs, a cognitive robotic with vision-based system is designed to remove the printed circuit boards and the mercury containing backlights, which poses a human health risk [5]. Regarding the extraction of battery, a robotic system named Liam was designed in 2016 by Apple to address the challenge of iPhone dismantling. Today, 1.2 million iPhones can be dismantled per year using this system [6]. Furthermore, an improved robotic system named Daisy was launched by Apple in 2018, which can deal with nine different versions of iPhones [7]. However, it is worth noting that Daisy acts as a prototype and there was only one unit operating in 2019. To explore the potential to disassemble batteries from electric vehicles with high-voltage risks, a battery system from the hybrid Audi Q5 was studied to determine the necessary tools and disassembly sequences [8]. In later research a robotic disassembly workstation was used to execute repetitive tasks, such as loosening of the screws [9]. However, prior research only demonstrated the feasibility of dismantling the batteries of a single product model or specific brand models and cannot be adopted to dismantle batteries of a broader range of product models. In addition, for the majority of products it is not considered economically viable due to the high reverse logistics cost to centralize all products of a specific series or even brand when reaching their end-of-life [10]. In addition, the methods developed for the automated dismantling of TVs cannot be transferred to the case of battery dismantling, as this system makes use of an angle grinder, which would result in a high risk of fire incidents. Therefore, the techno-economic feasibility of developing a generic robotic system for the removal of batteries from WEEE should be investigated. The presented research focuses on the dismantling of batteries from tablets, as they contain Li-ion batteries which are prone to fire incidents, because they have fairly uniform external designs and require a labor intensive dismantling process.

In this paper, a novel robotic dismantling system for battery extraction from the tablet is presented that can cope with a large set of different tablet models. In section 2, first 47 tablets are collected to analyze the feasibility of different dismantling strategies, then the current manual dismantling process for tablets is studied at a recycling company in Belgium. According to the analysis results, a robotic dismantling system is investigated to extract batteries from tablets. Section 3 presents the results of the designed robotic system based on another randomly selected set of tablets. Finally, the conclusions and future work are presented in Section 4.

2. Materials and Methods

2.1. Data collection

Due to the large variety in the tablet designs, the dismantling strategies differ a lot between different brands and models. In order to determine a prospective general approach and evaluate the corresponding performance, two different samples were randomly collected in 2020. The first set contains 47 tablets, which were disassembled manually to assess the visibility of the brand and model, as well as the necessary steps and tools required to remove the batteries from these tablets in the proposed robotic dismantling system. The second set contains 60 tablets, that were dismantled by the robotic dismantling system to evaluate its performance and efficiency.

2.2. Manual dismantling

Manual dismantling is the most commonly used methodology to dismantle tablets. In order to investigate the current manual strategy and the time needed for manual disassembly, an analysis of the current process was conducted at a large scale recycling plant in Belgium. A human operator with substantial experience with the dismantling of tablets was filmed over the course of 2.5 hours performing the manual dismantling using only a large flat screwdriver as a tool. In order to estimate the most time-consuming steps in the disassembly process. This resulted in time measurements for 282 tablets.

2.3. Robotic dismantling system

In this section, a novel robotic dismantling system is designed to extract batteries from tablets. The purpose is to minimize the work for the human operator, improve the working environment, and promote a safe recycling process. From the knowledge gathered from earlier works [11, 12], as well as from the manual process, the following three crucial tasks need to be executed for battery extraction: opening of the back cover, loosening of the connections and extraction of the battery.

2.3.1. Opening of the back cover

The robotic dismantling system consists of a Stäubli RX 160 HD with a pneumatic parallel gripper (Schunk 0371104). The payload of this robot is 20 kg at nominal speed, which is enough to perform all the designed experiments. Inspired by the actions performed by the human operators at Galloo, where the tablets are bent from the middle, a robotic bending setup is designed to open the back cover of the tablets. To carry out this bending process, a specific 2-finger gripper is designed (see Fig. 1(a)). The 2-finger gripper consists of one short and one long finger. The longer one acts as a support to counteract the

a b

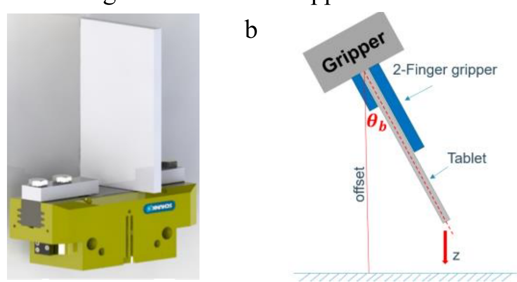

Fig. 1. (a) The 2-finger gripper; (b) The bending process

forces exerted by the bending process, and its end bends the tablet, while the shorter one holds the tablet and avoids covering the battery, which is essential for its extraction. Fig. 1(b) depicts the setup used for demonstrating the proposed bending system. For safety reasons, before executing the bending process, the tablet's length L should be measured to determine the maximum displacement of the robotic arm along the z-axis and, thus, prevent collisions. In order to facilitate the opening of the back cover, an optimal angle θ_b between the tablet and vertical z-axis needs to be determined on the basis of the bending results.

2.3.2. Loosen of the connections and extraction of the battery

Once the back cover is removed, the following phase of the dismantling process consists of the removal of the battery. In order to avoid puncturing those batteries fixed to the tablet by glue and to make it easier to separate these batteries, an experiment with a heating gun was conducted to evaluate the feasibility of loosening the glue that fixes the batteries. In this experiment, a Weldy S plus heat gun with heating temperature ranging between 60°C- 650°C was selected (see Fig. 2(a)). Thermal runaway of lithium-ion batteries occurs when the battery shell exceeds 200°C, and the subsequent uncontrolled exothermic reactions can cause the battery to catch fire or even to explode [13]. Therefore, the temperature of the hot air produced by the heat gun is set to 150°C. As depicted in Fig. 2(b), the heat gun is placed a few millimeters above the battery, and then slowly moved to evenly heat the battery surface.

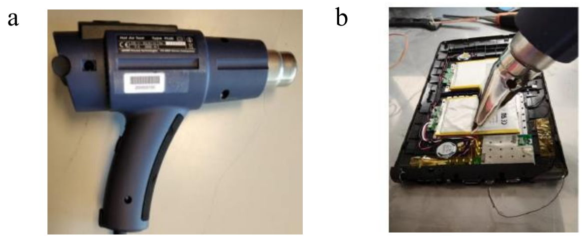

Fig. 2. (a) Weldy S Plus heat gun; (b) The heating process

Apart from the heating experiment, also a robotic scraping procedure was designed to separate the battery from the adhesives and the rest of the tablet. The same robotic setup was used as for the bending test. A flexible putty knife (9 cm width) was used as a spatula to separate the battery from the rest of the tablet. This spatula was mounted in a hinge, which can be adapted (see Fig. 3). Similar to the bending process, the best inclination angle θ_S of the spatula was evaluated during the scraping process. Furthermore, the position of the battery relative to the tablet was measured and calculated manually to determine the scraping path. With this information, the tablet is moved under the spatula and the spatula is pushed between the tablet and the battery. Then, the gripper moves downwards

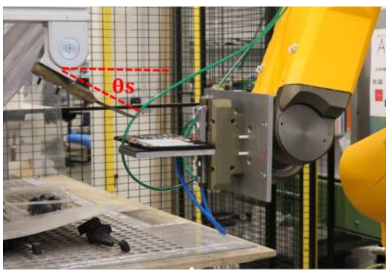

Fig. 3. Setup of the robotic scraping process

until the spatula is slightly bent to make sure that the shear force is sufficient to destroy the glue connection. Subsequently, the tablet is moved horizontally towards the spatula until the end of the battery is reached. If the battery is still attached to the tablet after this procedure the battery is further disassembled manually.

3. Result and discussion

The manual inspection of the 47 tablets indicated that only 19.15% of the model series numbers are readable, while 61.7% of the model brands are visible, as shown in Table 1. This indicates that the identification of the model through label recognition is impossible. In addition, 95.74% of the tablets have plastic as predominant material at the back side and that only iPads' back covers are made of aluminum. This turns to be an advantage since plastic is fragile and easy to break when highly bent. Furthermore, these analysis showed that batteries are fixed to the screen in nearly 90% of the collected tablets. This implies that the majority of the tablets should be opened from the backside to facilitate access to the batteries. The main types of connections used to fix the batteries are screws (6.38%) and tape (63.83%), whereas almost all the tablets (97.87%) had glue to secure the battery within the devices.

Table 1 Analysis result of 47 tablets.

Visibility of the brand	61.70% visible	38.3% not visible
Visibility of the model number	19.15% readable	80.85% not readable
Side to which the battery is attached	10.61% backside	89.36% front side
Backside material of the tablet	95.74% plastic	4.26% aluminum

In the manual dismantling process, the time needed for disassembly is known to strongly depend on the experience and routine of the operator. Nonetheless, considering a high level of experience of the operator still when working at 100% efficiency an average time of 28 seconds was found with a large variation among product models. One of the extreme cases is the iPad (Apple), for which the average disassembly time is 40 seconds. Its dismantling takes more time because its design is obviously different with respect to the back cover material and the fact that the battery is attached to the back side. Based on the manual dismantling of 282 tablets, the process can be split into 5 main steps:

- Take the tablet and bend
- Remove the backside
- Loosen the battery
- Cut connection wires (if present)
- Sort dismantled materials

An overview of the average time of the different disassembly steps is shown in Fig. 4, where bending the tablet, removing the backside, and loosening the battery consumers most of the time (85.17%). Accordingly, the proposed robotic dismantling system should focus on performing these three complex and time-consuming tasks.

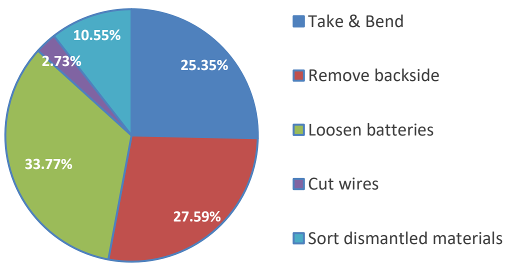

Fig. 4. Average time usage in the manually dismantling process

Regarding the robotic bending experiment, the results showed that it is easier to open the back cover with the long gripper finger on the tablet backside, because when the front of the tablet faces the long gripper finger, the fragile screen acts as a buffer and the structure of the back cover is more flexible if bent forward. Furthermore, during the experiments, it was found that by setting a value of 25° for θ_b, it is easier to create an opening of a few centimeters for 97% of the tablets between the back cover and the rest of the tablet. After partially opening the tablet, the back cover still needs to be removed from the tablet manually. For this, a flat screwdriver should be used to remove the back cover, which should also be considered for automation in future research by grasping the back cover and screen and pulling them apart. In the performed experiments, the manual time needed for removing the opened back cover accounts for about 5 seconds per tablet.

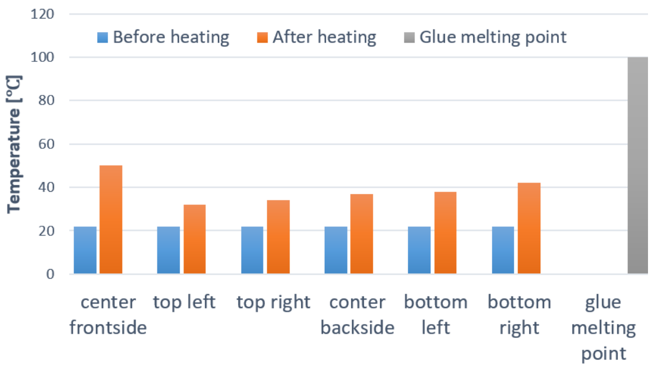

Fig. 5. Temperature distribution across the front and backside surface after heating the battery with a heat gun at 150°C.

For the heating gun experiment, the temperatures were measured at the center of the battery on the front side, as well as on the top left, top right, bottom left and bottom right corner before and after heating. As shown in Fig. 5, the highest temperature around the battery after 60s heating is 54°C, which is far lower than the glue melting point of 100°C. The results indicate that loosening glue with a heating gun as an auxiliary to facilitate the dismantling process is not feasible, because it is a time consuming process.

Based on the loosening conditions of the batteries after the robotic scraping experiment, the second set with 60 tablets can be divided into three different categories: not loosened, partially loosened and completely loosened. About 64% of batteries can be loosened completely. The challenging in this loosening step is that, in addition to glue, a battery can be attached to the tablet by tapes and screws, which results that 13% of the samples are partially loosened and that a 23 % cannot be loosened at all. As depicted in Fig. 6, four main problems can be summarized in the connections loosening process:

- The spatula gets stuck on an uneven surface between the battery and the tablet.
- The battery gets punctured.
- A part of the battery is fixed also by tape or screws, leading to only partially removal.
- The battery is highly integrated in the tablet, making it impossible to reach the battery with the spatula.

To tackle these issues, a different scraping tool and robot

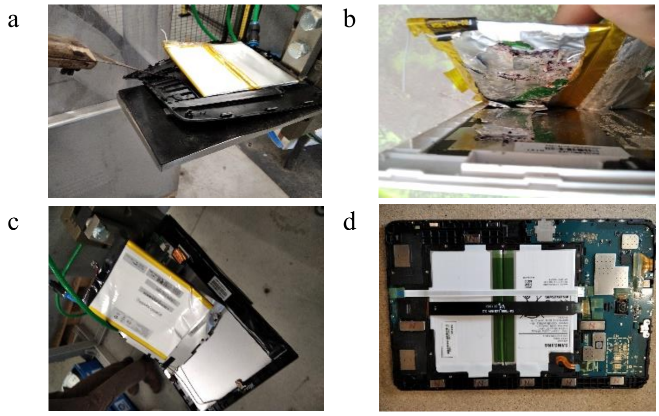

Fig. 6. Problems in robotic scraping process: (a) Unevenness surface underneath; (b) Puncturing the battery; (c) Partially loosening; (d) Highly integrated battery

toolpath should be adopted depending on the product model dismantled.

For the entire dismantling process, the dismantling time largely depends on the speed of the robot. Due to safety reasons, the dismantling procedures have been carried out with the speed of the robot limited to 50% of its maximum and the toolpaths adopted were not yet optimized. The average time for the robotic bending conducted with those restrictions is 27.6s and for the removing of a battery with the spatula is 53.8s. It should be pointed out that the battery extraction of the iPad is still a challenge for both manual and automatic dismantling. Although the number of iPads account for only 4.26% of the current investigated tablet samples, it cannot be ignored that the Apple iPad had a 31.9% share of the global tablet market in the second quarter of 2021 [14], which indicates that battery extraction methods for iPads will become of increasing importance in the forthcoming years. Therefore, specific dismantling strategies for iPads should also be investigated.

Furthermore, it should be considered that during the developed dismantling process, several manual steps are still required. For example, during the process of loosening the battery, the position of the battery relative to the tablet is currently manually measured and calculated. In order to further reduce the percentage of human operation in the dismantling process, the proposed system can be optimized by means of a robust computer vision and deep learning system, which has already been validated for the detection of the location of batteries in x-ray transmission images [15].

4. Conclusions

In this study, a set containing 47 tablets was collected and analyzed to investigate where their batteries are placed and how they are attached within the tablet. Through an investigation on the manual dismantling process as performed in a large scale recycling company, the most time consuming tasks in the tablet dismantling process are identified: tablet bending, back cover removal and battery loosening. Based on the learnings of these analysis, a robotic system was designed to extract the battery from tablets. The results show that the robotic system can facilitate the opening of the tablet back cover in the majority (97%) of the cases. Furthermore, experiments with a hot air gun demonstrated that heating the battery to loosen the glue is too time consuming. Therefore, experiments were performed with a spatula to scrape off the battery. Results demonstrate that the developed robotic system is able to loosen the battery in the 63 % of cases.

In case the automated dismantling is not successful manual task are still needed both for the removal of the back cover and battery. Therefore, future research will investigate to which extend the manual operations are facilitated, as well as the overall economic viability of the envisaged man-machine collaborative dismantling system. Additionally, due to the similar structure of mobile phones and tablets, the dismantling process will be adapted for mobile phones and extra experiments will also be carried out to verify the applicability of the designed robotic dismantling method for these product categories.

Furthermore, to increase the efficiency and success rate of automated dismantling operations, a different scraping tool and/or robot toolpaths will have to be adopted depending on the product design. Therefore, the feasibility of using recognition and retrieval algorithms will be investigated, as well as how to construct a database in which relevant information, such as back cover material, battery position and the types and locations of the fasteners attaching the battery to the tablet, can be retrieved for optimizing a robotic dismantling system after recognizing the product model .

Acknowledgements

The authors acknowledge Bert Vanelslande and Jan Van Rompaey for their contribution to this study in the context of their master thesis project.

References

[1] Larsson, F., Andersson, P., Blomqvist, P., & Mellander, B.-E. (2017). Toxic fluoride gas emissions from lithium-ion battery fires. Scientific Reports, 7. https://doi.org/10.1038/s41598-017-09784-z

[2] Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. (2006). In Official Journal of the European Union (pp. 1–14). Retrieved from http://data.europa.eu/eli/dir/2006/66/oj

[3] Duflou, J. R., Seliger, G., Kara, S., Umeda, Y., Ometto, A., & Willems, B. (2008). Efficiency and feasibility of product disassembly: A case-based study. CIRP annals, 57(2), 583-600.

[4] ARDUIN, R. H., CHARBUILLET, C., BERTHOUD, F., & PERRY, N. (2017). Life cycle assessment of end-of-life scenarios: tablet case study.

[5] Vongbunyong S, Kara S, Pagnucco M. A framework for using cognitive robotics in disassembly automation. In Leveraging technology for a sustainable world 2012 (pp. 173-178). Springer, Berlin, Heidelberg.

[6] Rujanavech, C., Lessard, J., Chandler, S., Shannon, S., Dahmus, J., & Guzzo, R. (2016). Liam-an innovation story. Apple Inc.: Cupertino, CA, USA.

[7] Bogue, R. (2019). Robots in recycling and disassembly. Industrial Robot: the international journal of robotics research and application, 46(4), 461–466. https://doi.org/10.1108/IR-03-2019-0053

[8] Cerdas, F., Gerbers, R., Andrew, S., Schmitt, J., Dietrich, F., Thiede, S., ... & Herrmann, C. (2018). Disassembly planning and assessment of automation potentials for lithium-ion batteries. In Recycling of Lithium-Ion Batteries (pp. 83-97). Springer, Cham.

[9] Wegener, K., Chen, W. H., Dietrich, F., Dröder, K., & Kara, S. (2015). Robot assisted disassembly for the recycling of electric vehicle batteries. Procedia Cirp, 29, 716-721.

[10] Islam, M. T., & Huda, N. (2018). Reverse logistics and closed-loop supply chain of Waste Electrical and Electronic Equipment (WEEE)/E-waste: A comprehensive literature review. *Resources, Conservation and Recycling*, *137*, 48-75.

[11] Schischke K, Stobbe L, Scheiber S, Oerter M, Nowak T, Schlösser A, Riedel H, Nissen NF. Disassembly analysis of slates: design for repair and recycling evaluation. Fraunhofer IZM: Berlin, Germany. 2013.

[12] Talens Peiró L, Ardente F, Mathieux F. Design for Disassembly Criteria in EU Product Policies for a More Circular Economy: A Method for Analyzing Battery Packs in PC‐Tablets and Subnotebooks. Journal of Industrial Ecology. 2017 Jun;21(3):731-41.

[13] Ma, S., Jiang, M., Tao, P., Song, C., Wu, J., Wang, J., Shang, W. (2018). Temperature effect and thermal impact in lithium-ion batteries: A review. Progress in Natural Science: Materials International, 28(6), 653–666.

[14] Tablet and Chromebook Shipments Continue to Surge During the First Quarter, According to IDC, https://www.idc.com/getdoc.jsp? Container Id=prUS47648021

[15] Sterkens W, Diaz-Romero D, Goedemé T, Dewulf W, Peeters JR. Detection and recognition of batteries on X-Ray images of waste electrical and electronic equipment using deep learning. Resources, Conservation and Recycling. 2021 May 1;168:105246.