Electronic waste management: A review of the limiting factors and robotic solutions

Elektronik-Altgeräte-Management: Eine Übersicht der limitierenden Faktoren und Roboterlösungen

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***Abstract* —** According to the Global E-Waste Monitor 2020 [1], in the year 2019, nearly 53.6 million metric tons (Mt) of e-waste (excluding PV panels) was generated, but only 17.4 % was formally collected and recycled. In this article, the limiting factors, which have led to these low recycling rates, will be examined as well as the state-of-the- art robotic solutions applied in practice today. Lastly, a novel method for improving the e-waste management system, based on multirobot collaboration, was proposed.

***Zusammenfassung* —** Laut dem "Global E-Waste Monitor 2020" [1] wurden im Jahr 2019 fast 53,6 Millionen metrische Tonnen (Mt) Elektronik-Altgeräte (ausschließlich PV-Module) erzeugt, jedoch wurden davon nur 17,4 % offiziell gesammelt und recycelt. In diesem Artikel werden die limitierenden Faktoren, die zu diesen niedrigen Recyclingquoten geführt haben, sowie die heute in der Praxis eingesetzten State-of-the-Art Roboterlösungen untersucht. Schließlich wird eine neue Methode zur Optimierung des Elektronik-Altgeräte-Managementsystems vorgeschlagen, die auf der „multirobot collaboration" basiert.

I. INTRODUCTION

"There is 100 times more gold in a tonne of mobile phones than in a tonne of gold ore" [2, p. 5]. Additional support for this claim arrives from Kumar *et al.* [3] who state that the concentration of metals in e-waste is significantly higher than that found in natural ores from which these metals are extracted, and almost 130 times higher in the case of gold.

Despite such findings, 43.7 million metric tons of e-waste are still undocumented and unknown [1]. Forti *et al.* [1] estimate that around 8% of global e-waste is disposed of in general waste bins, leading to environmental pollution and material loss due to the fact that it is landfilled or incinerated. Furthermore, a significant amount of e-waste, in the range of 7% to 20%, is exported for informal disposal in developing countries where its improper treatment presents significantrisks to both the environment and human health. According to [4], some of these risks are the release of heavy metals such as mercury and lead, as well as greenhouse gases discharged from cooling and freezing equipment.

Most experts agree that e-waste is a hazardous material that can be turned into a valuable economic resource if properly reused or recycled [1] – [4]. However, current trends show an increase in the generation of e-waste, which according to [5] could reach 110 Mt by 2050. To gain a better understanding on this issue, we must first define what e-waste actually is.

A. E-Waste Definition

E-waste is a broad term which does not currently have a globally accepted definition. Some experts simply define it as "anything with a plug, electric cord or battery… that has reached the end of its life, as well as the components that make up these end-of-life products." [2]. However, such ubiquitous definitions do not illustrate just how broad and varied the "fastest growing waste stream in the EU" [4] truly is, nor how customers determine when a product has reached the end of its useful life. These are just two of the factors which significantly contribute to the e-waste management problem.

The terms e-waste and waste electrical and electronic equipment (WEEE) are used interchangeably throughout the literature and differ from the term electrical and electronic equipment (EEE). To gain a full understanding of what e-waste is, the terms EEE and WEEE need to be further defined. For the purposes of this article, the definitions found in the European Union's (EU's) WEEE directive [6] will be used. This is owed to the fact that Europe is the global leader in e- waste recycling, with 42.5% of its generated e-waste documented to be collected and properly recycled [1]. According to the directive, EEE stands for:

> equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1000 volts for alternating current and 1500 volts for direct current [6, p. 3].

In the same document, WEEE is defined as:

> electrical or electronic equipment which is waste within the meaning of Article 3(1) of Directive 2008/98/EC, including all components, sub-assemblies and consumables which are part of the product at the time of discarding [6, p. 4].

It is worth mentioning that this directive does not apply to some EEE. Most notably, to batteries and type-approved vehicles, because batteries are covered by the Batteries Directive [7, p. 7], whereas type-approved vehicles, such as cars and planes, are excluded in order to differentiate between them and those which are not type-approved, such as electric rollers and electric bikes [7, p. 29].

Since the global quantity of e-waste is made up of many different types of EEE, which contain unequally harmful and unequally valuable materials, it is important to classify the EEE nto categories which will make the e-waste more manageable [8].

B. *E-Waste Classification*

There is no globally accepted standard for classifying e-waste; however, there are some effective examples.

In Japan, the Home Appliance Recycling Law increased the country’s recycling rates to approximately 55%, after being introduced in 2001 [9]. It classifies e-waste into 4 categories: (1) televisions, (2) refrigerators, (3) washing machines and (4) air conditioners [10].

However, in the EU, from the 15th of August 2018, the WEEE directive classifies all EEE into 6 different categories (EU-6) [7]: (1) Temperature exchange equipment, (2) Screens and monitors, (3) Lamps, (4) Large Equipment (any external dimension greater than 50 cm), (5) Small equipment (no external dimension greater than 50 cm) and (6) Small IT and telecommunication equipment [6, p. 26].

The differences in how countries classify e-waste overcomplicate its management on a global scale. These different classifications, however, are comparable to each other and can be interpreted as subparts of a broader classification which includes all available EEE. One such classification was created by Wang *et al.* of the United Nations University and is called UNU-KEYS [11]. This classification can be used to sort all WEEE items into 58 categories which are organized based on three perspectives: “product type (functionality and industry sector), waste management (return stream characteristics) and legislative relevancy (material composition, hazardous and valuable content)” [11, p. 1].

The ability to categorize WEEE based on its functionality, weight, and material contents makes the UNU-KEYS classification valuable not only for statistical purposes, but also for computer vision algorithms which require clean data to perform object recognition.

C. *E-Waste Management*

According to Premalatha *et al.*, all e-waste management strategies must be built around the following three imperatives: (1) Reduce the generation of e-waste, (2) Develop cleaner methods for the production, operation, and disposal of e-goods, and (3) Develop technology for the gainful use and disposal of the accumulated e-waste [10, p. 1619]. These strategies correspond to the waste management hierarchy known as “Lansink’s Ladder”, proposed by Dr. Ad Lansink in 1979.

Lansink’s Ladder is a sequence of management options ordered from most to least environmentally desirable: Prevention, Reuse, Recycling, Recovery and Disposal [12]. This hierarchy also holds true in the context of e-waste management, where the main goals are to reduce the generation of e-waste and recover its valuable materials with the overall goal of reducing the negative impacts of e-waste on the environment and therefore on human health.

The following chapters will examine the e-waste management processes, the limiting factors, and the robotic solutions for each step of Lansink’s Ladder.

II. Preventing E-Waste

In [2, p. 6] the authors state that “designers, manufacturers, investors, traders, miners, raw material producers, consumers, policy-makers and others have a crucial role to play in reducing waste”. To gain a better understanding of this complex issue, the relations between the main stakeholders, as well as the underlying processes of e-waste management were graphically summarized in Fig. 1.

Starting with EEE producers, the management of e-waste begins before the product has even been manufactured with the environmentally oriented product design imposed by the Extended Producer Responsibility (EPR) concept. The EPR concept was first introduced in Germany in 1991. It aims to prevent the generation of e-waste by extending the producer’s responsibilities beyond a product’s useful life, from the early design phase until the final disposal [10]. “An example is to design a product in a way that it is energy efficient during use, generates less waste and especially hazardous waste at end-of-life, and facilitates recovery, reuse, and recycling” [10, p. 1621]. Many countries have based their e-waste legislation on the EPR concept [10], which has led many companies to make global commitments to design products without hazardous materials and keep waste out of the electronics value chain [2].

Consumers are also major stakeholders in e-waste recycling, along with governments, producers and recyclers [9]. Ultimately, it is the consumers who determine when an electronic product has reached its end-of-life. Consumers are responsible for properly disposing of their e-waste, for example in recycling containers [13] or by returning the product to its producer through a take-back system [10]. In some countries, consumers are also the main financers of the recycling system [9]. For example, in Switzerland, consumers have to pay a recycling fee upfront, whereas in Japan “consumers have to pay an end-of-life fee that covers part of the recycling and transportation expenses” [10, p. 1627].

Educating consumers about their role in e-waste management can reduce the generation of e-waste and increase formal recycling rates. In [14, p. 1] the authors present the EDUCABOT3D project, which seeks “to raise awareness among students and the community about reducing the bad disposition [disposal] of electronic waste, through environmental education, using an informative booklet and teaching robotics”.

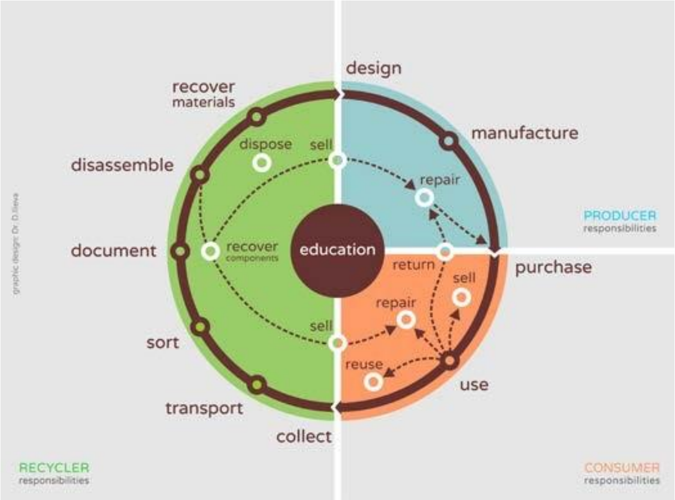

Fig. 1. E-waste management processes and responsibilities

III. Reusing E-Waste

Namias (2013) claims that “Reuse, refurbishment or repair of electronic products is [the] most desirable [EoL option] since this option increases the lifespan of the electronic product in order to achieve greater resource efficiency.” [15, p. 7]. An important aspect of reusing EEE is to separate the working products from the damaged ones and to evaluate the performance of the product [16]. These tasks are still too complicated to be automated and require manual labor.

When the whole product cannot be reused, some of its components might still be reused. Li *et al.* state that in the United States “The dismantling process has yielded more components for reuse in secondary markets." [17, p. 930] compared to the shredding process. Wang *et al.* agrees, stating that "Separating the reusable components [of desktop computers] can definitely bring extra profit to the dismantlers" [18, p. 2139]. Reusing components can not only be profitable but also energy efficient, as Hellwig states "it is more energy efficient to salvage an aluminium heat sink from a de-manufactured device and re-use it, than it is to fabricate a new one from virgin materials." [19, p. 6].

Robots can be used in the disassembling process to salvage reusable components. For example, Apple's robot systems Liam and Daisy are capable of disassembling iPhones and sorting their components, such as the rear camera, speaker, main logic board, etc. [20]. Another possible robotic solution is to reuse e-waste by building functionally limited robots for educational purposes as suggested by Bula *et al.* [21].

IV. RECYCLING E-WASTE

According to Kumar *et al.*, the three main reasons for recycling e-waste are economic, environmental, as well as public health and safety [3]. The economic benefits include the value of recovered materials, the generation of electrical, and thermal energy and the creation of jobs [22], [3]. The environmental benefits include reduced water, soil and air pollution, by properly treating hazardous materials, and reduced greenhouse gas emissions due to the significant energysavings gained from recycling rather than producing new metals [3, p. 36], [22]. The public health and safety benefits arethe reduced risks of adverse health effects associated withunregulated e-waste recycling such as adverse effects on the cardiovascular, respiratory and immune system [1, p. 64]. Namias (2013) confirms this by stating that "Recycling of electronics allows for precious and special metals to be recovered, reduces the environmental impact associated with electronic manufacturing from raw materials, and ensures that hazardous and toxic substances are handled properly." [15].

E-waste recycling is generally divided into two stages, pre-processing and end-processing. Pre-processing includes the processes sorting, disassembling, shredding, mechanical separation and grinding into bulk powder [3], [19]. The goals of pre-processing are to remove hazardous materials and separate the various material streams such as metals, glass, andplastics [3]. End-processing includes pyrometallurgical, hydrometallurgical and biometallurgical processes, which aim to "recover valuable metals from the concentrate obtained after pre-processing and [are] mostly used to recover and purify copper, gold, silver and palladium" [3].

One reason for the low recycling rates is the complexity of the e-waste stream. It contains up to 69 elements from the periodic table [1], however, it is mainly composed of metals (~60 % weight) and plastics (~15.21 % weight) [23]. To reduce the complexity and preserve the quality of the materials, the e-waste stream must be sorted, and the individual products disassembled before moving onto more destructive processes like shredding and grinding.

The limiting factors, which inhibit the effective robotic sorting and disassembling of WEEE, are the variety of the products, their design, which is not optimized for easy disassembly, and their lack of machine-readable features. In the context of recycling lithium-ion batteries from electric vehicles, Harper *et al.* state that the use of "adhesives, bondingmethods and fixtures do not lend themselves to easy deconstruction either by hand or machine." [12, p. 84]. They goon to say that recent computer vision algorithms are capable ofrecognizing objects and materials based on their physical characteristics; however, it could be beneficial for the recycling process if manufacturers included "labels, QR Codes, RFID tags or other machine-readable features on key battery components and sub-structures" [12, p. 77]. Although focused on batteries, the same points can be made for other e-waste product types. In fact, an interesting parallel can be drawn between lead-acid batteries and other EEE and that is standardization. As the authors note: "lead–acid batteries are relatively standardized and simple to disassemble and recycle, which minimizes costs, allowing the value of lead to drive recycling."[12, p. 84]. If the same cannot be done for other electronic products, which depend on their unique design to drive sales, then a new solution is required which will produce similar results. One such solution is proposed in the Discussion section of this article.

Nevertheless, some robotic solutions have managed to overcome these challenges and automate the sorting and disassembling processes.

A. Robotic Sorting

E-waste can be sorted by many different attributes such as product type, material content, size, etc. "Optisort" is a system which uses computer vision algorithms to recognize and sort AA and AAA batteries according to their chemical composition [12], [24]. E-waste can also be sorted depending on the condition of the products. The WEEE ID project funded by VINNOVA (Swedish Agency for Innovation Systems) partnered with ReFind Technologies to develop an intelligent, automated sorting system which "uses sensors and intelligent data processing to detect almost in real time whether used electronic products are good for reuse, refurbishment or recycling, and sorts them accordingly" [25, p. 460]. Another way to sort e-waste is by its material contents. Gundupalli *et al.* developed a procedure based on thermal imaging which classifies e-waste materials into 4 categories: metal, plastic, glass, and printed circuit board (PCB). They report a classification success rate in a simulated e-waste stream in the range of 84 – 96% [26].

B. Robotic Disassembling

The automated disassembly of WEEE is a complex problem which does not have a generic solution. However, some producers of EEE have been able to develop product- specific disassembly robots. For example, Apple's Liam and Daisy robot systems. The Liam system is comprised of 29 robots capable of disassembling an iPhone 6 phone into 8 discrete components in 11 seconds [27], while the Daisy robot is claimed to be capable of disassembling nine versions of the iPhone with a rate of 200 devices per hour and with greater efficiency, compared to existing techniques, such as shredding [20]. In addition to its speed and efficiency, Apple claims that the Daisy robot can "recover materials that traditionalrecyclers can't" [20, p. 22]. Similarly, Marconi *et al.* developed a prototype for a cost-effective robotic cell capable of desoldering components from a PCB without damaging them [28].

Human-robot collaboration relies on human dexterity to disassemble complex fixtures and robot precision to safely remove hazardous materials. Veolia's RoboTele system puts this theory into practice by using human operators and robots to disassemble LED and LCD TVs and remove the mercury tubes from the latter. The system is "aimed at dismantling upto 500,000 flat screen LED and LCD TVs per year" [29, p. 464]

Reconfigurable recycling systems (RRSs) "are defined as systems with the built-in ability to rearrange or modify their recycling processes to adapt to the specific characteristics of a waste stream" [30, p. 748]. Barwood *et al.* have demonstrated an RRS, based on the Staübli RX160 robotic arm, capable of semi-destructive disassembly and separation of electric vehicle components, e.g. electronic control units and PCBs [30].

V. Recovering Materials From E-Waste

After the hazardous and reusable components have been separated, the e-waste enters the end-processing stage with the goal of recovering its valuable materials. To achieve this goal, the e-waste undergoes a hydrometallurgical, biometallurgical, or, more commonly, a pyrometallurgical process [31], which presents a challenging working environment for robotic systems. Nevertheless, robots are also prevalent in the metallurgical industry. For example, they can be used in the forging process to manipulate the shape of the recovered metals [32].

VI. Disposing of E-Waste

Disposing of e-waste in landfills must be avoided due to the environmental and health hazards that would create as well as the loss of valuable materials. However, Forti *et al.* estimate that "Around 8% of the [global] e-waste is discarded in waste bins and subsequently landfilled or incinerated" [1, p. 14]. That is why some researchers are analyzing how robots can help in the garbage collection process, to separate e-waste from household waste [33], while others are focused on how robots can be used to localize gas emission sources when the e-waste has reached the landfill [34].

VII. Discussion

The variety of WEEE makes the automatic disassembly of its components a significant challenge. This has a negative impact on global e-waste recycling rates and the quality of recovered materials. Some researchers are attempting to generalize the capabilities of robotic disassemblers to a variety of objects using AI technology, but this "remains a major challenge at the frontier of artificial intelligence research" [12, p. 77]. The current state-of-the-art, however, shows that robots are capable of disassembling similar types of products [20], [27] and robotic arms have been proven to be effective tools for sorting heterogenous objects [35], [29]. Therefore, it mightbe possible to achieve practical results sooner by developing ane-waste sorting method which is optimized for the purposes of robotic disassembly.

Based on this literature review, it can be determined that the e-waste stream can be classified and sorted into 58 distinct categories, according to the UNU-KEYS classification, and that e-waste sorting systems must be able to handle small equipment, large equipment, and temperature exchange equipment, because these are the three most common e-waste categories [1, p. 24]. Furthermore, [9] and [30] have stated that future recycling facilities must be modular, scalable, mobile, integrable, flexible and cost-efficient, which excludes the use of large, heavy and expensive industrial robots. Therefore, this paper proposes the development of a multirobot collaboration system comprised of compact robotic arms, capable of quickly sorting small equipment and collaboratively sorting heavier equipment. This system would require a computer vision model trained to recognize e-waste products according to the UNU-KEYS classification. This would allow the robots to not only sort the e-waste, but also document it in a statistically valuable manner. The proposed method for autonomous sorting and documentation of e-waste will be further developed in a future article.

VIII. Conclusion

In this article, the e-waste management problem was correlated to the waste management hierarchy, also known as Lansink's Ladder, and reviewed from five aspects: Prevention, Reuse, Recycling, Recovery and Disposal of e-waste. The limiting factors for each process were examined, and the state-of-the-art robotic solutions were presented. The conducted research found that there is a need for automation solutions in the recycling industry; however, the complexity of the e-waste stream has proven to be a significant challenge for the current robotic systems.

The main contributions of this article are the graphical summary of the e-waste management processes and responsibilities found in Fig. 1 and the proposal of a novel method for autonomous sorting and documentation of e-waste based on multirobot collaboration.

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