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Review

Robotic disassembly for increased recovery of strategically important materials from electrical vehicles

J. Li*, M. Barwood, S. Rahimifard

Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, UK

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ABSTRACT

The rapid growth of market share of Electrical Vehicles (EVs) and their increasing amount of electric and electronic components have introduced difficult challenges for future recycling of such vehicles. End of Life Vehicles (ELVs), together with Waste Electric and Electronic Equipment (WEEE), are renowned as an important source of secondary raw materials. In addition, a significant proportion of the hidden value at the End-of-Life (EoL) of the EVs is embedded in the light fractions containing complex material mixtures, i.e. the management of electronic components that has been rarely considered in the scientific literature. The purpose of this paper is to fill this gap through the use of an innovative disassembly approach to identify the profitability of recycling such electronic components. The novel approach, based on the utilisation of a robotic system, disassembles and extracts Strategically Important Materials (SIMs) from EV components, thereby improving the concentration of these materials prior to final recycling and refining processes. This paper presents the challenges in the robotic disassembly of Electrical and Electronic (E&E) components. A case study has also been included to demonstrate that an average 95% of the materials and their associated recovery value could be achieved.

1. Introduction

The rapid growth in the number of traditional vehicles with internal combustion engines has increased the demands for fossil fuel and exacerbated their environmental impacts [1,2]. Driven by government incentives and customer desire for more fuel-efficient and cleaner forms of transportation, an ever-increasing number of alternative fuel vehicles have been introduced to the global automobile market, ranging from natural gas, fuel-cell and hybrid electric to electric vehicles (Fig. 1) [3]. The use of such alternative fuel vehicles is thought to be a vital part of future sustainable transportation policies; thus, it is predicted that the production of these vehicles is set to further increase. Both the volume and the content of the waste generated by the automotive section however make ELVs one of the most significant sources of EoL products [4]. The total number of ELVs in the EU-27 was 9 million in 2009 and in the UK is 2 million in 2014 [5,6]. It is predicted that the generation of waste ELVs will be 19.5 million tons in 2020 [7,8].

It is noted that one of the key differences in the design of EVs is the significantly larger number of E&E components that involve the management of almost all functionalities of the vehicles [9]. Therefore, this trend would lead to an increase in the production of Printed Circuit Boards (PCBs) and the generation of waste PCBs that need to be recycled and recovered. Additionally, an increasing range of materials is required as part of these electronic devices, often referred to as SIMs, i.e. Precious Metals (PMs) and Rare Earth Elements (REEs).

On average of all traditional and alternative fuel vehicles 15 E&E components are embedded in a modern standard medium-sized car but this number can rise to 48 in a luxury car, including microcomputers and Electronic Control Units (ECUs) [10–12]. They are used to read and process signals from various sensors, to control the performance of the sub-systems, such as engine, air-bag and air-conditioning systems [13]. It is also estimated that the value of the automotive electronic components can account for 30% to 50% of the cost of some vehicles [12]. The automotive electronic components can be seen as a special type of e-waste whose majority of their environmental impacts is caused by the recycling of PCB. It consists of complicated materials, including heavy metals, e.g. lead, chromium, cadmium; toxic substances, e.g. brominated flame retardants; and valuable materials, e.g. gold, silver and palladium [14].

Current EoL treatment for automotive ECUs is non-existent, and they are simply left within ELVs which are sent for shredding and material recovery. However, this inappropriate recycling method results in a serious environmental impact arising from the discarding of hazardous materials, and poor economic performance due to the loss of the valuable materials that are in small quantities, i.e. SIMs. This evidence highlights the importance of recovery of these automotive electronic components in regards to both the embedded value and environmental aspects.

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* Corresponding author.
E-mail address: jieli43@hotmail.com (J. Li).

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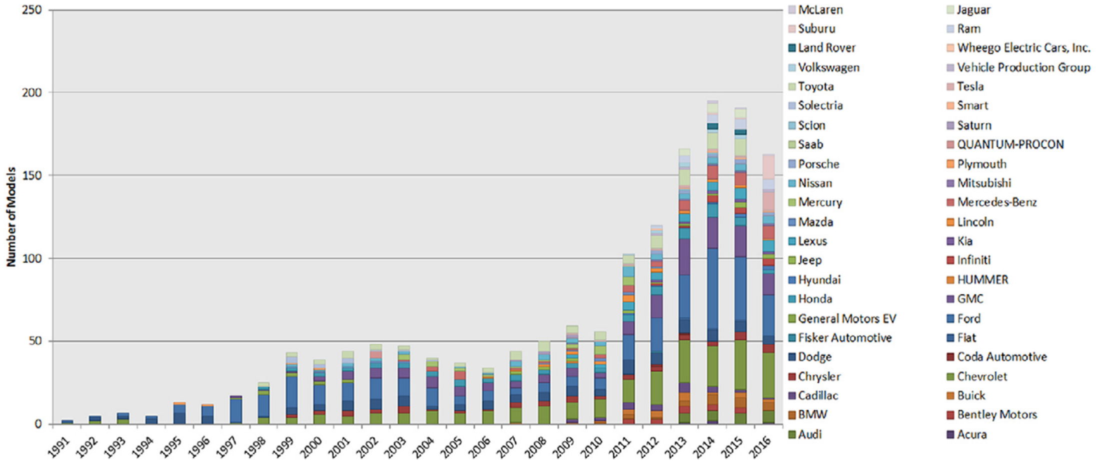

Fig. 1. Growth of alternative fuel vehicles models [3].

Given the national and international legislative requirements, the global ELV recycling industry has been established in different countries. Direct management systems have been designed and developed in the European countries, China, Japan and Korea. The EU-Directive 2000/53/EC on ELVs was introduced with specific recycling and recovery targets. EU Member States, e.g. Denmark, Netherlands, Belgium, Finland have established detailed rules on compliance with this Directive in different ways [15]. In China, the ELV recycling regulations enacted in 2001 with the introduction of an ELV collection system [15]. The Law for ELV recycling was enacted in Japan in 2005 to promote the reduction of Automotive Shredder Residue (ASR) [16]. Furthermore, the action for Resource Recycling of Electrical and Electronic Equipment and Vehicles has been enforced in Korea in 2008 [17]. Additionally, driven by market mechanism, an indirect management system has been built for ELVs in the US. Current vehicle recycling activities are predominantly based on automated fragmentation and separation processes which are designed for recovering basic metallic contents (e.g. steel, aluminium and copper) that often represent a significant proportion of weight (>70%) of traditional vehicles [18]. Increased amount of advanced and lightweight materials has been used in modern vehicles to improve the fuel economy and maintain the safety and performance, such as high-strength steel, aluminium alloys, carbon fibre and polymer composites [19]. It is evident that vehicle material composition has moved away from metals and transitioned more toward lighter materials.

In comparison, although SIMs content presents a substantial proportion of the hidden value contained in modern vehicles, it often represents a much smaller proportion of the weight of vehicles (<5%) [10]. It has also been identified that the research on the EoL management of the scrap automotive electronic (i.e. ECUs) is very limited [20].

The potential for developing an appropriate recycling approach for the automotive electronic components contained in EVs has been identified in this research. The recycling approach should be able to liberate and extract sensitive and valuable materials i.e. SIMs, from these components. Thus, this paper highlights a need for the development of bespoke EoL management technologies and processes tailored to the specific requirement of EVs.

In this context, a number of researchers have investigated a range of automated approaches for disassembly and improved concentration of valuable materials, prior to final recycling and refining processes. Michalos et al. [21] discussed the application and benefits of robotic technologies in automotive assembly. Duflou et al. [22] have reviewed various disassembly practices and highlighted the importance of automation techniques as well as tooling and fixturing systems for achieving flexibility and robustness of disassembly processes. In relation to this, a number of research projects have proposed the use of robotic systems in disassembly of electronic products. Knoth et al. [23] have developed an intelligent robotic disassembly process which utilised a vision system to identify components for extraction, and was capable of removing components based on a series of simple robotic processes. Basdere and Seliger [24] have explored the use of robots within a flexible disassembly and recovery line for large and small size electrical consumer goods. Vongbunyong et al. [25] have also proposed the concept of “cognitive robotic system” for disassembly of LCD screens and TVs, utilising a vision system, and have highlighted further flexibility and configurability challenges to deal with multi-product designs. In Korea, a smart dismantling monitor and trolley system has been developed to facilitate remote real-time monitoring of the dismantling status in each workstation [17]. Wegener et al. [26] have focused on disassembly of the batteries in hybrid cars and have proposed as their future work, investigation into the use of robots in this application. Wegener et al. [27] have also presented a concept of hybrid human robot disassembly workstations for EV battery disassembly, in which the assisted robot performs simple and repetitive tasks using provided location information. Pintzos et al. [28] proposed an approach for generating relevant disassembly information based on design files for disassembly line planning. Radaschin et al. [29] presented a concept of a product-driven control system to cope with the disassembly object variety, different product conditions and amounts. In terms of the estimation of recyclability, Papakostas et al. [30] developed a computer–aided design assessment which enables designers and engineers understand the recyclability of the designs in the first phase of the EoL management. Feldmann et al. [31] touched upon the issue of disassembly costs and highlighted the difference in recycling costs and benefits between various materials fractions.

The research reported in this paper aims to build upon the existing work in this area and to specifically address the flexibility and reconfigurability challenges in dealing with a varying size of components from EVs. The paper is structured as follows; Section 2 of the paper provides a brief review of relevant literature and an overview of current vehicle recycling and recovery practices. Section 3 presents a framework for assessing EoL requirements for EV components, and describes a robotic disassembly approach for recycling of components within EVs in order to maximise the value recovery and minimise the environmental impacts. The applicability of the framework is demonstrated in Section 4, the case study. Finally, Section 5 presents concluding remarks and future perspectives.

2. EoL vehicle recycling

2.1. Overview of EoL vehicle recycling

Due to financial incentives and legislative requirement in relation to the ELV Directive, there has been a significant investment and improvement in vehicle recycling systems. Although the exact processes may vary marginally in various countries, a typical flow diagram of the current recycling and recovery route for ELVs is illustrated in Fig. 2.