Robots in recycling and disassembly

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Abstract

Purpose – This paper aims to illustrate the growing role robots are playing in recycling and product disassembly and provide an insight into recent research activities.

Design/methodology/approach – Following a short introduction, this first considers robotic waste sorting systems and then describes two systems for the disassembly of electronic products. It then provides details of some recent research activities. Finally, brief conclusions are drawn.

Findings – Robotic systems exploiting artificial intelligence combined with various sensing and machine vision technologies are playing a growing role in the sorting of municipal and industrial waste, prior to recycling. These are mostly based on delta robots and can achieve pick rates of 60-70 items/min and be configured to recognise and select a wide range of different materials and items from moving conveyors. Electronic waste recycling is yet to benefit significantly from robotics although a limited number of systems have been developed for product disassembly. Disassembly techniques are the topic of a concerted research effort which often involves robots and humans collaborating and sharing disassembly tasks.

Originality/value – This provides an insight into the present-day uses and potential future role of robots in recycling which has traditionally been a highly labour-intensive industry.

Keywords Disassembly, Robots, Recycling, Waste

Paper type Technical paper

Introduction

An inevitable consequence of population growth, urbanisation and economic development is the increased creation of waste. The global municipal solid waste generation level is presently estimated at approximately 1.3 billion tons/year and is expected to increase to around 2.2 billion tons/year by 2025 and 3.4 billion tons/year by 2050. Electronic waste (e-waste) is the fastest growing sector and comprises products such as computers, tablets, displays, TVs and phones which contain valuable and toxic materials alike. An estimated 50 million tons of e-waste are produced each year, the US annually discards 30 million computers and 100 million phones are disposed of in Europe each year. The US Environmental Protection Agency estimates that only 15-20 per cent of e-waste is recycled, the remainder enters landfills and incinerators. The total value of the materials present in all e-waste in 2016 was estimated at approximately €55bn.

For environmental, economic and ethical reasons these waste generation levels have led to a massive growth in recycling, a global industry now worth around $280bn. This often involves highly labour-intensive processes, particularly when waste requires sorting or products require disassembly prior to material recovery and recycling, but the industry is investing heavily in automation, including a limited but growing use of robotics. This article aims to illustrate the role robots are playing in recycling and disassembly and to provide an insight into recent research activities.

Robotic sorting of municipal and industrial waste

Effective municipal and industrial waste recycling relies heavily on effective sorting which is traditionally a highly labour-intensive, tedious and potentially hazardous practice. Many automated systems have been developed which can separate individual materials such as metals, paper, glass and plastics from waste streams and use techniques such as magnetic, eddy current, inductive and near-infrared (NIR) sensing methods but these can only separate a specific product or material. There is mounting pressure for more, and more effective, recycling and thus sorting; in the EU for example, EC Waste Directive 2008/98 stipulates that 50 per cent of all household waste and 70 per cent of all construction waste must be reused or recycled by 2020.

Robotic solutions have been developed which can separate several different materials from waste streams, a technology that was pioneered by Finnish ZenRobotics. Founded in 2007 and building on scientific work conducted by the neurorobotics research group at Aalto University, it was the first company to launch a commercial, robotic waste sorter, in 2011. Its present products, the Heavy Picker (Figure 1) and Fast Picker (Figure 2) use a combination of artificial intelligence (AI), machine learning and computer vision to pick and sort items from waste streams on moving conveyor belts. Key to this is sensor data fusion. The Heavy Picker uses NIR sensors, a 3 D laser sensing system, a high-resolution RGB camera, an imaging metal detector and a visible light sensor while the

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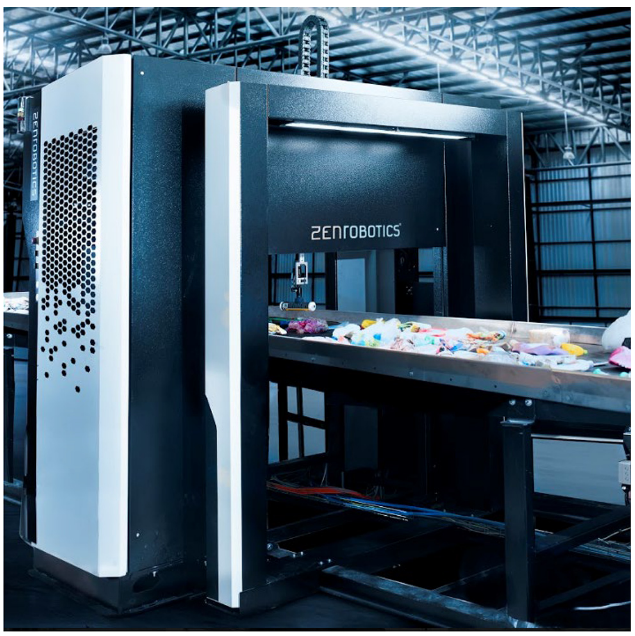
Figure 1 The heavy picker

Source: ZenRobotics

Figure 2 The fast picker



Source: ZenRobotics

smaller Fast Picker uses an RGB camera and LEDs. The Heavy Picker is the strongest waste sorting robot on the market and is aimed at heavy and bulky items such as building materials, wood, metals and rigid plastics (see video clip at: https://youtu.be/-Xc8J1O5uoI). It is able to separate objects weighing up to 30 kg, the gripper opens to 500 mm and it can be equipped with from one to three robotic arms with a maximum speed of 2,000 picks/hour/arm. The Fast Picker sorts lightweight materials such as paper, plastics, cardboard and other packagings and is equipped with a single arm with a payload capacity of 1 kg and has a maximum speed of 4000 picks/hour. These and the company's earlier products are now operating in around 10 countries in Europe, North America and the Far East.

A more recent market entrant is AMP Robotics which was founded in 2014 and received financial support for the development of a waste sorting robot from both the private and public sectors. These included the National Science Foundation and the Carton Council, an organisation founded in 2009 to develop solutions to divert valuable cartons from disposal in landfill. AMP's product, the Cortex, is a robotic picking system that uses an ABB delta-style robot and low cost visible light cameras which feed images to a computer which employs advanced machine learning algorithms to recognise items on the conveyor. It uses suction cups as grippers and has demonstrated a pick rate of 60 items/min and has been taught to recognise over 150 carton types. In late 2016, AMP started trials with the system to identify and sort food and beverage cartons through collaboration with the Carton Council and Alpine Waste & Recycling. A second system was installed later that year to sort similar cartons at Dem-Con Companies, a Minnesota-based waste recycling, processing and disposal company.

Canadian waste recycling specialist Machinex Industries has collaborated with AMP on the development of the SamurAI waste sorting robot (Figure 3); AMP provided the artificial intelligence while Machinex provides all the robotic components. The system also uses a delta robot and has maximum payload of 6 kg and can achieve up to 70 picks/min using a suction tool and has a product recognition rate of up to 95 per cent. The first robot was installed in 2018 at Lakeshore Recycling Systems at its Heartland Recycling Centre in Illinois. Located on the container line after a magnet and an optical sorter which ejects PET (polyethylene terephthalate), the robot picks three types of products: coloured HDPE (high-density polyethylene), natural HDPE and aseptics (previously sterilised containers). A short video showing the system in operation can be viewed at: https://youtu.be/2OY80BwaJH8. Several systems have since been ordered for use in Canadian waste sorting centres.

Another recently developed system is the Max-AI AQC, produced by Oregon-based Bulk Handling Systems, a company founded in 1976 and specialising in processing systems, including optical sorters, to extract recyclable materials from waste streams. Launched in 2017, the Max-AI

Figure 3 The SamurAI robot

Source: Machinex

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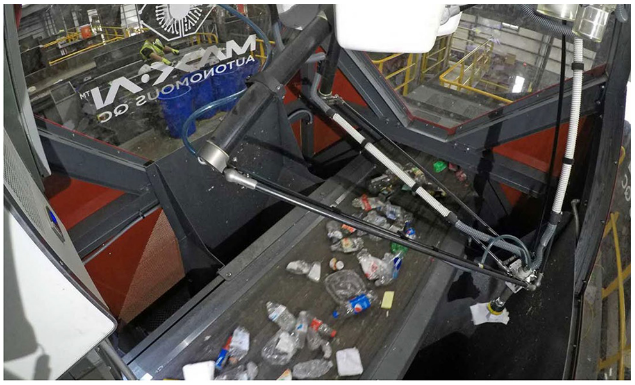
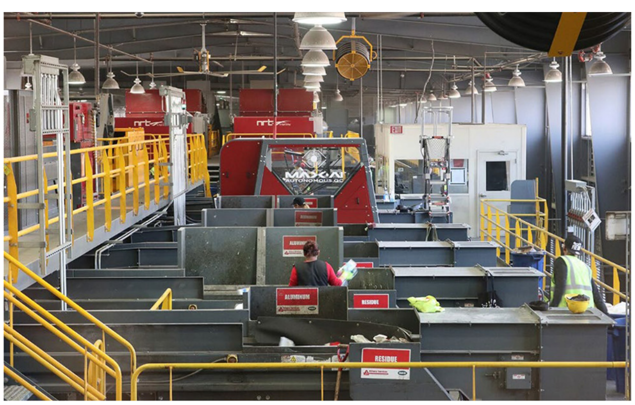
Figure 4 The delta robot picking items from a conveyor



Source: Bulk Handling Systems

AQC uses machine vision and multi-layered neural networks and a delta robot (Figure 4) to sort waste with a pick rate of about 65 items/min. It can sort plastic containers and film, cardboard, paper, aluminium and steel cans and cartons and can act as a quality control tool by, for example, separating thermoform trays, aluminium, fibres and other residue from a stream of optically-sorted PET bottles. The first unit was installed at Athens Services' materials recovery facility in Sun Valley, CA (Figure 5) where it is used to complement the screen, air and optical separation technologies already in use. Integrated with the company's existing optical sorters, the system provides a fully autonomous PET sorting capability. In addition to this and several other installations in the US, continental Europe and Asia, two systems have recently been installed in the UK: at Green Recycling in Essex and Viridor in West Lancashire. The Green Recycling system (Figure 6) will be used on a recovery line to capture card, newspapers and pamphlets, natural HDPE, PET bottles and wood while the Viridor system is sorting and applying quality control to plastic bottles. This facility in Skelmersdale recycles 3,000 tons of post-consumer plastic bottles per month into high value raw materials. The primary recyclate streams are PET and HDPE which are of sufficient quality to be used in the most demanding applications as a direct replacement for virgin polymer.

Figure 5 The Athens services installation



Source: Bulk Handling Systems

Figure 6 The system installed at green recycling

Source: Bulk Handling Systems

French robotics, machine vision and AI specialist Siléane (see below) also produces a robotic waste sorting system, the Kamido. This is based on the company's bin picking technology and in contrast to most other sorting systems, it uses 3 D vision and a conventional robotic arm rather than a delta design.

Dismantling electronic products: mobile phones and televisions

Consumer electronic products tend to be complex and difficult to dismantle and as noted above, much e-waste is not recycled, despite its economic value and is "dumped" in third-world countries where any material recovery is conducted with scant regard for operator safety or health. Thus, there is a pressing need for technologies that can automatically and safely dismantle e-waste products and recover their high value content.

Mobile phones have among the shortest lives of all consumer electronic products and approximately 1.46 billion are sold annually throughout the world and while some are resold, many are discarded. In the USA, 416,000 enter landfills or incinerators every day, where they release toxins such as heavy metals into the air, water and soil. Equally, they contain high value metals including gold, platinum, tantalum, titanium and tungsten, together with the scarce rare-earth metals neodymium, praseodymium and dysprosium, all of which warrant recovery. Thus, there are environmental needs and economic motivations for more recycling and in 2016 Apple announced the Liam robotic system which is capable of disassembling 1.2 million iPhone 6 units per year and recovering much high value material.

Described by Apple as an "R&D project focused on new disassembly technologies", the system comprises 29 articulated-arm robots on an conveyor line with 21 individual cells, with dual-robots used in those cells involving processes with particularly high cycle times. It removes the following from the phone: cover glass assembly, battery, main logic board, receiver, speaker, alert module, rear facing camera and housing. The system can dismantle a phone in 11 s and uses two main processes: conventional end-of-arm-tooling such as a drill bits and suction cups which interact with a stationary

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phone and robotic handling to position the phone so as to interact with external tooling. A video clip of the system can be viewed at: https://youtu.be/AYshVbcEmUc. Systems have been installed in California and The Netherlands but an improved version dubbed Daisy (Figures 7, 8 and 9) was unveiled in 2018. In contrast to its predecessor, it can dismantle nine different versions of the iPhone, at a rate of 200/hour. The system can determine the iPhone model and its degree of bend through vision recognition algorithms and rejects those with more than a 10 mm bend which the system cannot accommodate. The display is then removed, followed by the earpiece assembly which includes a magnet containing rare earth metals. To release the battery which is glued in place, a jet of air cooled to −80°C freezes it and the adhesive and a tool knocks it out. At this point, what remains is the phone's aluminium housing with one PCB with components attached with screws and five robotic arms, two reused from the Liam robot, then remove the screws. The final robot rotates the phone at a 90° angle and bores out the camera, speaker, haptics and remaining PCB assemblies with a single stroke and the components fall onto a conveyor. For every 10,000 iPhones disassembled, the following can be recovered: 190 kg of aluminium, 80 kg of copper, 0.13 kg of gold, 0.04 kg of platinum group metals, 0.70 kg of silver, 5.5 kg of tin and 2.4 kg of rare earth elements. Like Liam, however, Daisy is a prototype and so far there is just one unit operating in the USA but Apple states that it intends to install systems in "multiple locations around the world" beginning with a second system in Europe.

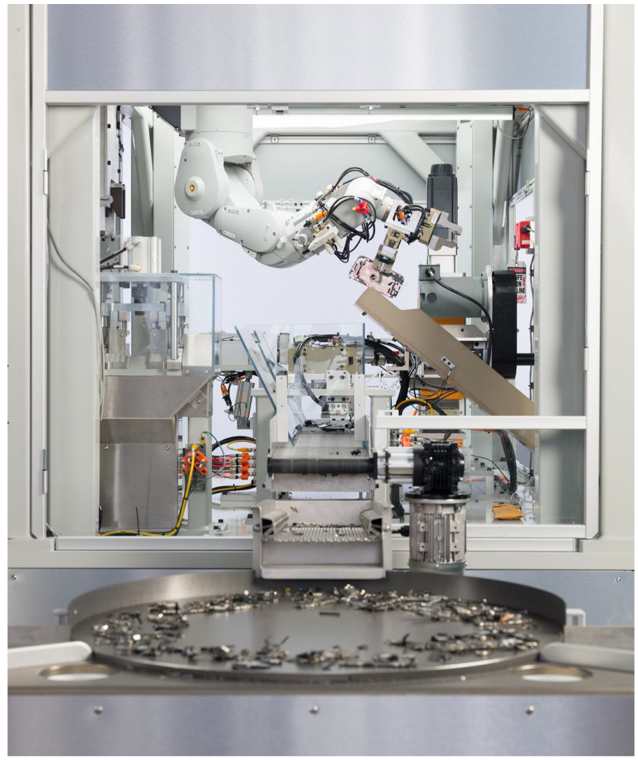
Figure 7 Feeding iPhones into the robot

Source: Apple

Figure 8 Removal of the display

Source: Apple

Figure 9 Sorting components for recycling



Source: Apple

As with phones, televisions contain both valuable and hazardous materials and their disassembly to recover materials for recycling is a complex task, undertaken by human operators. While a fully automated, robotic solution is yet to be developed, French water and waste group Veolia has deployed a system which combines robotic and human functions. Dubbed RoboTele, the purpose-built system was developed by Siléane and uses robots manufactured by Fanuc. It has been installed in the UK at Veolia's facility in Bridgnorth, Shropshire and is aimed at dismantling up to 500,000 flat screen LED and LCD TVs per year. First, the units have their speakers, plugs and accessories removed manually and are then sent to the first robot (Figure 10) which applies pressure to the four sides of the frame and removes the screen without damaging the case. After human operators have removed the top layers of the screen, LCDs are sent to a second robot which cuts the mercury backlighting tubes while injecting a wax mixture to prevent the release of the mercury. The tubes are then removed manually

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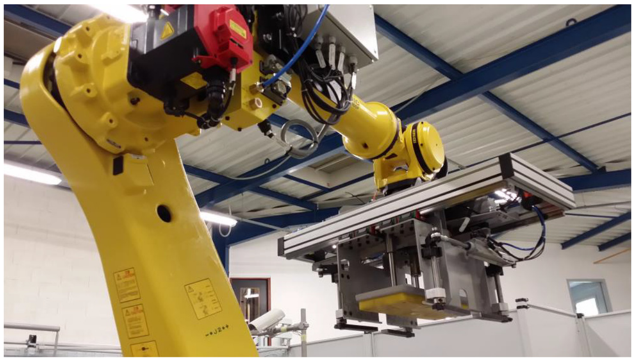
Figure 10 The screen removal robot



Source: Veolia

and sent to another facility for mercury recovery and the remaining shells enter a shredding and separation system. The LED units do not contain mercury and bypass the second robot and are sent directly to the shredding line. A video describing the system in more detail and showing it in operation can be viewed at https://youtu.be/4R1ejpKAnLM.

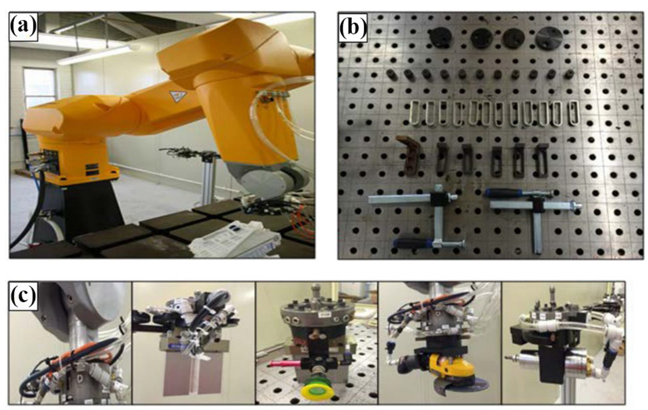
Some research activities

It is evident that, with the exception of waste separation, robots are yet to exert a significant impact in the recycling business. In part, this reflects that the majority of recycling practices presently place the main emphasis on the economic benefits and ignore environmental and social considerations, which is in contrast to the principles of sustainability. Reflecting this and recognising the lack of a systematic approach for assessing the trade-offs between environmental benefits, technological feasibility and the economic viability of robotic disassembly, workers from the Centre for Sustainable Manufacturing and Recycling Technologies (SMART) at Loughborough University have proposed a framework for the multi-criteria assessment of robotic product disassembly for recycling and recovery. A decision support tool has been developed to compare the results from different recycling scenarios based on manual and automatic disassembly. A set of six indicators has been proposed to assess the environmental, technological and economic performance of robotic disassembly and a simple normalisation approach has been applied to standardise these independent indicators and rescale them to values between 0 and 1. A laboratory-based robotic disassembly cell and three automotive electronic components with differing designs and material recovery values were used to evaluate the assessment tool and showed that it allows decision makers to compare the performance of different recycling scenarios and to identify the most appropriate and feasible option.

Reflecting the anticipated growth in fully electric and hybrid vehicles and the associated increase in electronics used in, and e-waste ultimately arising from, these, the SMART group has experimented with a 6-DOF industrial robot to dismantle and recover materials from automotive ECUs (electronic control units). This work demonstrated that on average 95 per cent of the materials and their associated value could be recovered. The group argues that, in order to keep pace with the technological advancements in electronic products and their material content, future robotic disassembly systems need to be highly flexible and reconfigurable. They have developed a prototype system based on Staübli robot, a standard modular fixturing platform and a specially designed set of tools (Figure 11), capable of drilling, milling, cutting and gripping using a pneumatic system. A series of ECUs used in electric vehicles (EVs) with various materials, constructions and sizes were successfully disassembled, the valuable materials were extracted and the potentially environmentally damaging materials separated for subsequent safe treatment. This work demonstrated that the system has the capability and flexibility to adjust its set-up and operational functions for different products and the ability to integrate additional robotic tools, other hardware and software modules.

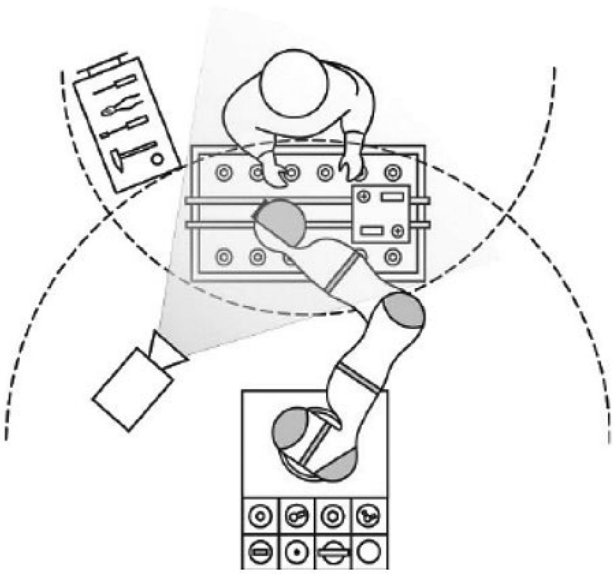
In addition to electronic modules, EVs will generate large numbers of battery modules, most probably lithium-ion types, for recycling. Workers from the Technical University of Braunschweig and the University of New South Wales have demonstrated a battery disassembly workstation (Figure 12) where a human is assisted by a collaborative robot (cobot), in this case a KUKA LWR (Lightweight Robot). While the human performs the more complex tasks, the cobot conducts the simple, repetitive tasks, namely the removal of screws and bolts. In trials, an Audi Q5 Hybrid battery system was used and two robotic bolt/screw location strategies were investigated: user-demonstration and autonomous detection using cameras. The results suggest that physical demonstration may be feasible but has the drawback of high time consumption, whereas automatic detection can speed up the process but

Figure 11 The robotic disassembly cell



Notes: (a) Staübli RX160 robot; (b) Divano 16-series fixturing platform with accessories; (c) customised pneumatic robotic tools including (left to right) tool changer, 2-finger gripper, air suction gripper, circular cutting saw and drilling/milling tool
Source: Barwood *et al*., "Utilisation of reconfigurable recycling systems for improved material recovery from e-waste", Procedia CIRP, 29, pp. 746-751

Figure 12 Schematic of the human/robot workstation



Source: Wegenera *et al*., "Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries", Procedia CIRP 29, pp.716-721

further work is required to develop a more accurate location algorithm.

This strategy of humans working alongside robots, whether conventional or collaborative, to share e-waste disassembly tasks and as successfully deployed by Veolia (above) is seen as offering the greatest prospects in the immediate term and is the topic a major EU-funded project, HR-Recycler. Running from late 2018 to 2022, with a budget of almost €7m and involving 12 European participants, this aims to develop systems whereby humans and robots will share and simultaneously undertake different e-waste processing and manipulation tasks such as waste categorisation, product disassembly and waste segregation. The primary output of the system will be sorted electrical/electronic device components and concentrated material fractions of economic value (copper, aluminium, plastics etc.) and the ultimate objective is to reduce today's almost total reliance on human labour.

Conclusions

Robots are yet to exert a major influence on recycling and disassembly practices, although systems exploiting artificial intelligence and machine vision technologies are playing a growing role in the sorting of municipal and industrial waste, prior to recycling. The robotic automation of e-waste recycling poses significantly technological challenges although a limited number of systems have been developed for product disassembly. E-waste disassembly techniques are the topic of a concerted research effort and the strategy of robots and humans collaborating and sharing disassembly tasks is viewed as offering the greatest prospects in the immediate term. Ultimately, this will reduce the heavy reliance on human labour in many monotonous and often hazardous recycling practices and also increase the quantity of materials recovered and the work on multi-criteria assessment of robotic technologies should stimulate the more widespread use of robots throughout much of the recycling sector.

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