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Collaborative robots in e-waste management

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Abstract

Nowadays manufacturing companies are going through an increasing public and government pressure to reduce the environmental impact of their operations. But when dealing with e-waste, some difficulties arise in classifying and dismantling electronic devices. Manual operations are financially prohibitive and full automation is also discarded due to the lack of uniformity of the disposed devices. A halfway solution is to let a human operator and a robot share the process. The goal of this research is the optimization of the recycling process of electronic equipments, applying both technical and economic criteria, and taking into account the latest developments in collaborative robots.

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Keywords: Collaborative robots, WEEE, recycling, circular economy, reverse logistics

1. Introduction

Although human beings and nature belong to the same vital flow and have a common future, our way of understanding progress is unsustainable, since natural resources cannot be regenerated at the same pace we are consuming them [1]. Nowadays manufacturing companies are going through a growth of social awareness, environmental regulations and international standards to reduce the environmental impact of their operations. In fact

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customers are changing their attitudes towards the products they buy, considering not only the acquisition cost but also how the products were made and under what working conditions, as well as how they are discarded at the end of their life cycle. There are recent examples such as the VW emissions scandal, variations in oil prices depending on the use of fracking technologies for extraction, or lack of raw materials for the manufacturing of high-tech devices causing environmental and social problems in third countries. They show that the consequences of ignoring the environmental effects of the manufacturing operations may cause unexpected results in the acceptance of a product.

In the last years, we are facing serious environmental problems related to the technological change and throw-away consumer culture in electronic equipments such as tablets, computers or phones which become obsolete very quickly. As a matter of fact, Waste Electrical and Electronic Equipment (WEEE) has been identified as one of the priority waste streams by the European Commission along with batteries, tyres, vehicles and packaging.

As a result, on the output side of production, the amount of electronic waste, also known as e-waste, increases dramatically. This mounting volume of e-waste must be disposed of at landfill sites that often lack capacity to discard it. Likewise, on the input side of the process, this phenomenon creates higher requirements of natural resources to produce more electronic devices. But natural resources are scarce due to continuous exploitation, even being sometimes close to depletion. Therefore there is a tension both at the input side of manufacturing due to increasing consumer needs and limited resources to fulfil them and at the output side of it owing to insufficient landfills to absorb residues. This tension can be reduced if the traditional linear economy is replaced by a circular economy, where the final user is not the end of the supply chain but some return processes are included to obtain value of discarded products. The circular economy requires new production schemes since we cannot afford to waste scarce materials and resources. The idea is that end-of-life products are not disposed of at landfills but returned into the same or other manufacturing processes in order to replace input materials or components that are normally extracted from natural resources or manufactured [2].

Until recently, and due to the economic crisis, the quest for higher employment rates seemed to fade the role of the circular economy, green manufacturing and use of recycled elements as source of raw materials. The aim was to encourage natural resource extraction and manufacturing activities regardless of their environmental impact, seeking for the reduction of unemployment. But what used to be taken as restrictions on economic activities in the past, is increasingly regarded as an essential element for the individual preferences and levels of quality of life, and thus emerges as new opportunities for development and improving competitiveness. Now the environment plays a core role in the people´s decisions: where to live, what to consume, or how to produce. As consequence, new business opportunities arise to reuse, remanufacture and recycle, therefore changing from a “cradle to grave” to a “cradle to cradle” paradigm. This transition may mean important resource and energy savings, less environmental impact of residues as well as sales enhancement by exploiting market opportunities related to the recycling sector [3].

Most waste management legislation is producer responsibility regulation that aims to increase product recycling by making producers financially responsible for their products at the end of life. Specifically the WEEE legislation focuses on improving the waste management processes, reducing hazardous materials and increasing recycling capacity [4]. A great deal of WEEE is also reused or recycled, thus obtaining valuable materials such as gold or copper and also saving much energy [5].

But when dealing with waste from electric and electronic equipment (WEEE), the barriers for the success of their recycling (technical and economic) are the difficulties in the classification and disassembly of components. The use of manual process operations is considered financially prohibitive and full automation is also discarded due to the lack of uniformity of the disposed devices.

2. E-waste management techniques

In order to implement a circular economy, the first step is to set up an effective reverse logistics system. In traditional supply chains forward logistics are concerned with material flows that go from suppliers to producers, over to distributors and then to customers. However reverse logistics are related to the return flow of end-of-life products, as well as subassemblies, components or materials that can be obtained from them [6]. Recycled components or raw materials can be used as secondary materials by suppliers and manufacturers at their manufacturing processes. In a similar way, recycled end products can replace new products for customers.

Therefore, waste disposal in landfill sites or incineration should be a last resort if no secondary use of a material is possible. In conclusion, a circular economy also includes the return processes trying to capture value out of it and also yielding significant environmental benefits.

E-waste management has to cope with some specific challenges [7]:

- The high cost associated to the collection and recycling of used products.
- The lack of harmonized cross-national legislation which means that a company must comply with regulations of varying rigour.
- The free-rider threat, i.e. companies importing products from countries having a less strict legislation, thus enjoying lower prices.
- Consumer awareness to return e-waste to separate collection points.

Reverse logistics applied to e-waste comprise different processes [8] (see Fig. 1):

- Collection and classification: includes activities of taking-back waste from different places of origin to separate collection points and splitting them into different groups which will undergo different measures of treatment.
- Warehousing: accumulates material in order to fully utilize transportation or processing facilities.
- Transportation: covers the distance between separate collection points and recycling plants.
- Recovery and reuse: results in the transformation of waste into reusable products.
- Product dismantling: disassembles the product into modules and components.
- Separation of materials: recovers both hazardous and valuable materials.
- Elimination of waste: transports non-recyclable waste to landfill sites or incineration plants.

Fig.1. Processes of reverse logistics.

With regard to waste management activities, the so-called ladder principle prioritizes reuse, remanufacturing and recycling over disposal with energy recovery or disposal in landfills (Fig. 2).

1. Direct recycling or reuse means that the product is used again for the same or a different purpose without major additional treatment.
2. Remanufacturing of parts or subassemblies implies that the product itself, its parts or subassemblies can be used again after some repair process.
3. Reprocessing of recycling material. In this case, products are disassembled into components which can be either directly reused or taken as raw materials for the same or inferior products.

4. Separation of material to a low level in order to obtain raw materials which can be used, after further processing, to produce new devices.

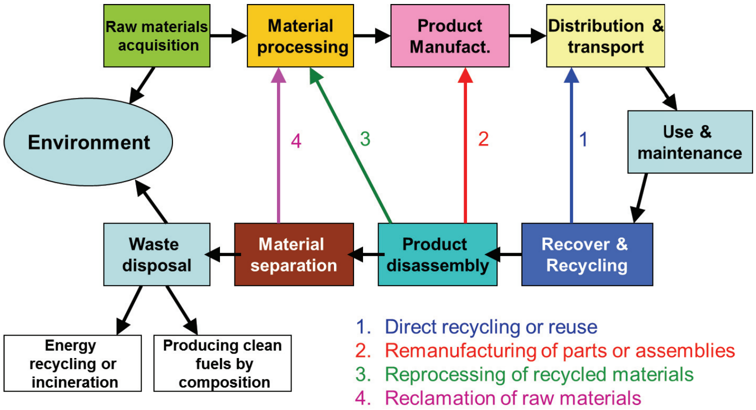

Fig.2. Different forms of recycling.

3. The limitations of automated techniques for WEEE

Regarding technical considerations, they are mainly related to the difficulty of finding a fully automated solution for dismantling electric and electronic devices. Firstly, a fully automated system requires a powerful identification system, with the aim of detecting different components and materials integrated in an electronic appliance. Apart from that, some kind of decision-support system able to select the best way to disassemble such appliance is also needed in order to extract its components in a suitable order.

Historically, task and process planning has been a field where researchers have developed methodologies to improve efficiency by defining and timing the optimal sequence of tasks in an operation [9]. In a traditional manufacturing process, the main objective is to finish a product on time and within costs limits. But, unlike manufacturers, whose goal is to meet deadlines for the delivery of products, in the world of recycling priorities are different. There is no due date, so there is little point in trying to comply with the time when the final "products" (raw materials or dismantled parts) are extracted from disposed devices. In the case of electronics recyclers, the main goals are to maximize revenues from the sales of recovered materials, and to maximize the space available in the area of the plant where waste is received and briefly stored immediately before it is recycled. This is because part of the income of electronics recyclers comes just from receiving shipments. But the arrival of shipments is unpredictable, so if the receiving area is full, incoming shipments have to be turned away or stored in trailers, causing a loss of income or incurring trailer rental fees. In order to solve this problem, several solutions have been suggested to maximize the recycling rate, giving priorities to different types of waste. Some recyclers try to keep their storing areas as open as possible by first processing products that can most quickly be taken apart. Another method consists of taking first the largest products that can be quickly disassembled. Others prefer to process the most valuable products first.

Following these procedures, several alternatives for planning of dismantling operations have been suggested. A method to optimize the material flow between the reception warehouse and the dismantling area was developed in [10]. In order to reduce recycling costs for computer monitors an optimization model was suggested in [11], by means of a procedure applied at two levels (product and product group), using a stochastic programming model. Later on, this model was generalized [12], proposing a dynamic programming algorithm to allow several disassembling partial processes.

A method for recycling was suggested in [13], based on two steps: the first one determines the automatic sequences of disassembly (in a virtual environment) and the second one identifies all the potential activities, according to the “target approach” method, transforming a multi-objective linear problem into a linear one. The use of linear programming is also present in [14], in order to obtain the optimal disassembly sequence.

Usual contents of electronic waste include metals and a large variety of resins and plastics, which can be coated, mixed with additives, and made flame retardant [15]. Regarding plastics recycling, the main concern is the need to identify and separate plastics found in electronics (mainly additives and contaminants). Several automated solutions have been proposed to separate a mixture of plastic and other elements, such as machine vision for image analysis [16] and vertical vibration systems. After correct separation, their properties (physical and mechanical) must meet those of virgin resins if they are intended to be used in high-end products. Nowadays, three types of recycling processes for plastics are being used. Firstly, chemical recycling processes use waste plastics as raw materials for petrochemical processes. Secondly, mechanical recycling is a conventional method, which uses a shredding and identification process to eventually make new plastic products. Thirdly, in thermal recycling, plastics are used as an alternative fuel [17].

Apart from the economic and technological points of view, other issues regarding employment should be taken into account. According to some impact assessment studies [18] the recycling of 10000 t of waste creates around 240 jobs, while incinerating creates 20 to 40 jobs, and landfilling about 10. In view of these challenges, in most cases combined recycling systems (integrating manual, semi-automatic and automatic operations) are applied.

4. A proposed solution for WEEE recycling: collaborative robots

Given the impossibility of full automation, and taking into account the importance of experience and skills of human operators, we propose the introduction of collaborative robots into the recycling lines. Traditional industrial robots perform their tasks in cages and are heavily dependent on hard automation that requires specified fixtures and time consuming programming, performed by experienced programmers.

One example of the use of this kind of robots for recycling is the disassembly of the iPhone mobile telephone by the Liam robot, developed by the Apple company [19]. The main objective is to obtain different parts of the phone in order to reuse and recycle them. For that purpose, the Liam robot detects the parts to be dismantled and then moves the phone to several workstations where, with the help of specific grippers or tools, the parts are separated from the main body. The robotized process is able to obtain lithium and cobalt from the battery, gold and copper from the camera, silver and platinum from the mother board and aluminum from the cover. In this case the robot works autonomously, because it is able to detect and apply the right process to each part of the mobile phone (which usually does not suffer big changes in its geometry during its life-cycle).

A different problem arises when dealing with bigger electronic appliances, such as washing machines, fridges, TV sets, etc. Their composition often includes cables, flexible parts or components difficult to identify. A skilled human operator could do this job (fig. 3), but the task is tedious and often dangerous if there are operations involving cutting or handling of hazardous materials.

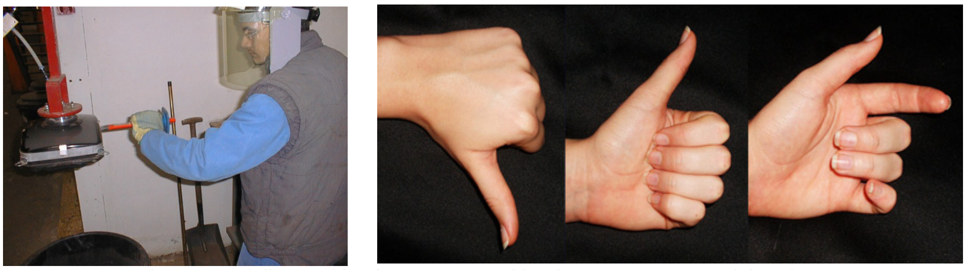

Fig.3. Manual disassembly of components and hand gestures to command the robot.

During recent years there have been several attempts of designing robots that are inherently safe and thus can work together with humans in mixed production lines. A recent example is ABB´s concept robot FRIDA. However, the internal pilot testing at ABB has shown that automation with FRIDA robots using traditional programming approach still takes a long time to accomplish. Such long integration times make the payback calculation for many potential applications challenging, and also prohibits the dynamic process setting with rapid changeover of operation conditions that the recycling field is seeking for.

In order to solve this problem, the collaborative robot should be able to learn the task from the operator. The worker will show the robot where to cut a cable or fixing, unscrew or manipulate a component, and where to discard it. The human operator may use her hand and fingers (fig. 3) to show specific reference points in the components, so the robot will use them to cut or take the part. Additional spoken instructions can be provided by the worker to instruct the robot with certain parameters. Therefore the robot will be able to recognize hand gestures such as “stop”, “go ahead”, “go to this point”, etc. For special cases where the reference points or sections inside the electronic device, where the visual clues are not clear enough for the robot, there is also the possibility of the operator taking the robot arm (in a passive mode), and leading it to these points to teach the tasks. Augmenting the robot with cutting-edge sensory and cognitive abilities as well as reasoning abilities will allow the execution of the disassembly task in close co-operation with the human worker. To reach this objective, visual tracking of the worker is required, directing attention to the relative positioning of the electronic device, its components, the worker´s body, arms and fingers.

5. Safety issues

In this human-robot collaborative scenario, the knowledge of the human position by the robot is of utmost importance. This is true not only for safety reasons, but also to be able to successfully interact with it. The solution proposed in the European Project COGLABORATION [20], to perform the human tracking, involves the combination of three techniques: body tracker, face recognition and segmentation by colour. These techniques complement each other in order to ensure the location of a human hand. One example of a device used to develop the perception modules is the RGB-D Kinect sensor. This system can be used to process the visual and depth information from the Kinect sensor and to extract the location of a person from it in front of the camera as well as an estimation of the location of her limbs, or her skeleton. The design of collaborative tasks requires providing some specific mechanisms to monitor the safety of the human partner, while the person is within the operation space of the arm, and in particular when potential contact can occur outside of the physical interaction protocol. In addition, there are other safety issues regarding the avoidance of dangerous physical interactions between robot and worker. The detection of such a risk is based on large variations of the commanded torques/motor currents in one or more robot joints. Therefore the collision is recognized, and the reaction not to allow contact is launched to the robot by stopping the motion reference generator.

6. Use Case

This concept has been applied to the recycling process of electronic scrap. The aim was to optimize the way to separate and recycle electronic appliances (specifically TV sets and monitors) in order to obtain the maximum quantities of raw materials at the lowest cost. One challenge was the re-use of the glass coming from old cathodic ray tubes and the valuable components coming from the printed circuit boards. Unlike iron, copper and aluminum, glass and plastics are difficult to extract, and reuse is not yet well resolved in new applications. Seeking a new application, a manufacturer of glazed tiles was identified as a potential user of the obtained glass.

Regarding the electronic components of the printed circuit boards, the aim was to recover and reuse the elements of high value (memories, transistors, condensers, etc), and to extract the hazardous components (batteries, etc). A robotized disassembling cell was set up, where a 6 axis industrial collaborative robot shares the workplace with a human operator. Operation in this cell is as follows: a transportation belt is used to enter CRTs into this cell. A vision-based system identifies the presence of lead in the panel glass, which determines further treatment of the CRT, sending appropriated commands to the robot and other machines. If the panel is lead free, the CRT must be separated in two parts: funnel and panel; otherwise it can be shredded without previous separation. The robot cooperates with humans in performing the first steps of separation. The worker shows the robot where to cut cables or take out small components, etc. After that, the robot uses a vacuum gripper to handle the CRT and transport it to next workstations, where a rotating saw cuts the CRT along the joining line between panel and funnel. Funnel glass and mixed parts (metal, silicone) fall in a container. Then, the robot moves to next station, only with panel part and metallic band. A similar operation is carried out, where metallic fraction falls in a container, and the robot carries the remains (panel glass) to a third container. Table 1 shows the obtained fractions of the recovered materials. A complete economic analysis of the robotized solution can be obtained in [21].

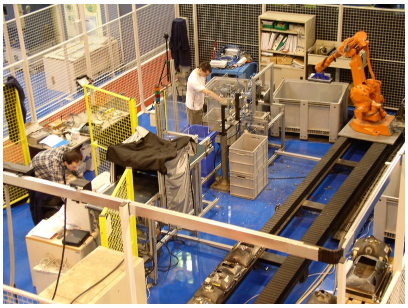

Fig.4. Robotized recycling line

Table 1. Average amount of materials recovered in a TV/monitor.

Material	Weight of material (kg)
Pannel glass	5.39
Funnel glass	2.50
Iron	1.47
Aluminium	0.04
Copper	0.69
Polyvinyl Chloride (PVC)	0.5
Condensers	0.005
General plastics	2.3
Mixed glass, silicon	0.45

7. Conclusions

New developments in collaborative robots allow for a close cooperation between humans and robots in a common working place, without fences between them. Thus the complexity of material and component identification could rely on the human side, while the more force demanding (and dangerous) tasks could be carried out by a robot. Current technical problems in the identification, classification, disassembling and manipulation of WEEE could be tackled by a combination of robotized and manual operations, where the human teaches a robot where to cut, separate parts, and the machine performs the low skilling operations. In addition, a smart transfer of tools and components must be achieved between human operator and robot.

The goal of this research is the optimization of the recycling process of electronic equipment, applying technical and economic criteria, taking into account new developments in collaborative robotics, and generating a model according to a dismantling strategy and degree of recovery that optimizes the profitability of the recycling. A significant step change required to fulfill the recycling targets of the EU and make the process profitable is the integration of robotic capabilities in the process, but combining it with a closer interaction with people. These interactions will become more physical and more intuitive over time, gesture, touch and spoken interchange will be the usual interaction between robot and worker.

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