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From e-waste to robots: a case study on e-waste upcycling in low-to-middle income countries

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Abstract—This paper provides details on a case study conducted into the upcycling of e-waste. E-waste is a global problem that is becoming an increasing burden on low-to-middle income countries. These low-to-middle income countries are the recipients of large volumes of e-waste per annum from higher income countries. In certain countries, precious metals are extracted from e-waste, however, this only marginally reduces the stockpiles of waste material, rendering much of it unusable. The objectives of this paper are to highlight the feasibility of re-engineering and upcycling e-waste as a workable route to waste management, using robotics as an example application area. Our methods included sourcing e-waste, identifying and isolating different usable parts from the waste, and re-engineering these into a flexible end effector with complete, coupled, rotational and translational freedom. We further develop active alternative control systems with passive elastic recovery. Our work shows there is feasibility in re-engineering e-waste to manufacture functional electro-mechanical products and devices, and that upcycling e-waste in this way is a step towards responsible e-waste management through engineering knowledge and practice. Our work also highlights some of the impracticalities and challenges involved in e-waste upcycling.

Index Terms—E-waste, Machine Design, Robotics, Kinematics, Actuation

I. INTRODUCTION

The UN Sustainable Development Goal 11, ‘Make cities and human settlements inclusive, safe, resilient and sustainable’, stipulates waste management as a key consideration in the development of sustainable cities. E-waste has become a growing concern in low and low-to-middle income countries (LMICs) as stockpiles of e-waste is routinely exported to LMICs as a means of reducing the burden of e-waste in higher-income countries. The Basel Action Network quite specifically pinpoints the UK as being the highest e-waste exporter in Europe to LMICs.

The global value of e-waste is estimated to be \$62.5 billion which is greater than the GDP of many countries in the world [1]. The Global E-waste Statistics Partnership (GESp) highlights that such waste has been increasing at a rate of 21% for five years to 2019, reaching an annual volume of 53.6 million metric tonnes per annum, nearly 8 kg of e-waste per capita, globally [2]. It is further expected to reach 120 million tonnes by 2050 [1] and additionally, only about 17%

of waste produced in 2019 is formally waste managed, and this statistic is true primarily in developed countries [2].

While some LMICs have crude methods for extracting precious metals from e-waste, such practices are hazardous and render the bulk volume of e-waste as unusable material destined for incineration. Yet, in e-waste, much of the electronics and materials are retrievable and reusable. This extraction process is inherently wasteful and the adoption of more sustainable practices (like upcycling) could not only ensure a larger portion of e waste is utilised, but may also offer more value than extracted precious metals. Hackerspace communities have been important in this respect and a few notable Hackerspace communities with a focus on e-waste upcycling already exist in LMICs. The Agboglobloshie Makerspace Platform (AMP) based in Accra, Ghana, has for example, been developing e-waste based upcycling strategies. With access to household, aeronautical, automotive and electronic scrap at the Agboglobloshie scrapyards, the Hackerspace community retains a philosophy of open air manufacture from e-waste, providing safe disassembly templates for a variety of common types of e-waste. Togo, also in West Africa, is another Hackerspace community (the Woelab) focussed on upcycling e-waste, and are looking to develop high-end tech from e-waste having already manufactured machines for additive manufacturing [3].

According to the World Economic Forum reports, half of the global volume of e-waste comprises day-to-day items such as computers and mobile phones, which are amongst the most commonly cited sources of e-waste that are designed for upcycling [4]. Using these is a logical starting point since not only do they have many useful components that are readily available in e-waste junkyards, but information on the specifications for each of the components is often easier to retrieve than for less regular e-waste items [5]. While a major segment of e-waste is recycled for metals [6], our philosophy is that even if precious metals are extracted, there is considerable further processing needed to re-work these into new technologies [7]. Our focus is on upcycling the e-waste technology that is already functional (or that requires only some adjustment), thus circumventing many of the processing requirements in materials extraction, while also enabling renewed technological development with the potential to benefit society. In this paper, we report on a case study conducted in Pakistan using day-to-day e-waste

items sourced from scrap facilities as a starting point for the development of a flexible, free moving robotic end effector. While our choice of a flexible free-moving end effector is simply to show the versatility and feasibility of re-engineering e-waste with the simplest of available tools and resources, specific use cases include any such cases where advanced manoeuvrability is desirable. Examples can include non-linear drilling and high-versatility endoscopes.

II. SOURCING OF HARDWARE AND MANUFACTURE OF FLEXIBLE END EFFECTOR

Information on the geographical and technological sources of hardware can be helpful as they contribute to global/local databases that are easy reference sources for the purpose of e-waste monitoring. Specific types of hardware were sourced from the Rex City scrapyards in Faisalabad, Pakistan, and these are shown in Table I. A reversible DC motor sourced from a computer CD ROM was used to generate a pulling force to enable bending of the soft robotic end effector. The end effector itself was a 3/4" PVC condensation pipe that was flexible enough to bend to an arc and rotate 360° around its axis, whilst concurrently being sufficiently stiff to recover from the deformation to its original state. Multiple tubular structures were analysed and the 3/4" PVC condensation pipe from an air conditioning unit was found to be most suitable given its ability to both flex and recover with relative ease. Once the flexible end effector was chosen, a wooden stock (ca. 2 inches in height) was taken and was lathed to fit snugly inside the tube, which would remain affixed to the base of the end effector when loaded and flexed. The wooden stock was then mounted on a flat wooden board as shown in Fig. 1(a).

TABLE I
SPECIFIC TYPES OF HARDWARE SOURCED FROM AN E-WASTE SCRAPYARD IN PAKISTAN.

Material	Specification	Prototype description
Reversible motor	DC motor	From scrap CD ROM
Power source	6-volt battery	Variable power supply
Corrugated tube	3/4" PVC condensation pipe	Common AC drain pipe
Thread	Nylon T-135	Multiplies twisted together
Thread guides	Stainless steel	Common paper clips
Assembly platform	Wooden board	Laminated chipboard
Control switches	Dbl. phase dbl. throw	
Wiring	Copper wires	Used wires from various types of e-waste
Nails and screws	Iron/silver	Suitable size length

A PC CD ROM was dismantled and a reversible motor separated along with its belt, a pulley and gear assembly to increase torque. These were modified by installing a round bobbin to the gear wheel to allow thread to roll on and off it as the motor was activated in its forward and backward directions, respectively. This was attached using a nylon thread to the flexible end effector to enable its kinematic motion. The modified motor assembly is shown in Fig. 1(b). Two identical motors were then sourced and mounted on a single platform so

that the nylon threads were attached to the soft end effector at the top at one end, with the motor assembly at the other end. The thread attached to top of the end effector was designed to run parallel to the vertical central axis, along the external wall of the tube and was further directed towards motor enabling a perfect right angle at the base of the end effector assemblage, and parallel to horizontal plane using stainless steel guides, as shown in Fig. 1(c). Guides were placed around the end effector at equal distances from and at 120° periods about the central axis of rotation. Threads were fed via the guides to the end effector and were connected to the motors as shown in Fig. 1(d).

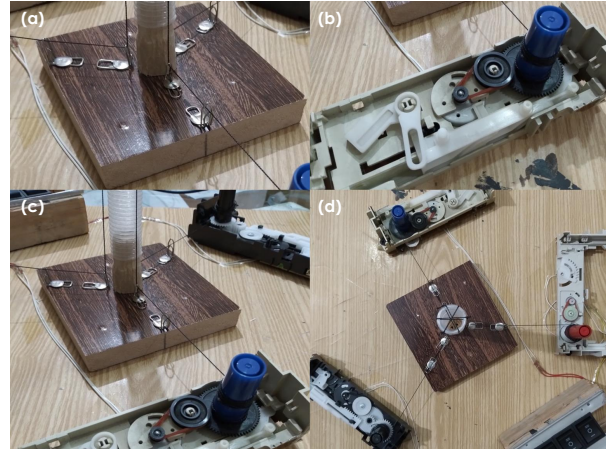


Fig. 1. (a) wooden stock mounted to a wooden board with end effector piping affixed to the stock (b) modified motor assembly (motors sourced from a PC CD ROM drive (c) thread-pulley-bobbin system connected to the end effector and the motor and (d) plan view of all sourced motors and their attachment to the flexible end effector.

Copper wires were used to drive individual motors through power transmission from a power source. Double phase double through (DPDT) switches allowed motoric movement in both, forward and reverse directions. As a result, the entire physical prototype comprising multiple sub-assemblies was ready to be driven. Individual motors were checked as to whether they could bend and release the end effector. Modifications needed to be made to the belts attached to the motor driven pulley to increase friction through increased tightness of the motor-pulley system. The prototype end effector made essentially from modified and re-engineered e-waste was able to conjointly translate and rotate to its full designed range of motion, much like the flexible arm of an octopus. The complete prototype can be seen in Fig. 2.

A. Development of an active control system

Since the active control system was developed outside of Pakistan another simpler mechanical prototype was made to test essentially, the viability of the software in controlling a flexible end effector. A pen cap was glued to the lowest reduction gear of the ejection drive, attached to the pen was a piece of string controlling the flexible end effector, inverted and then glued to the top of the pen cap was the potentiometer. A bracket was made by hammering one of the internal metal



Fig. 2. Complete set-up of hardware.

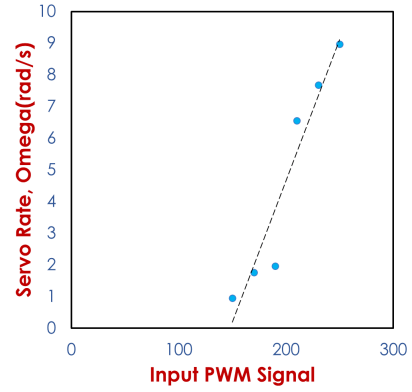


Fig. 3. Average rate vs input signal.

trays of the disk drive into a U-shape, following this a small off cut of wood was glued to hold the potentiometer in place. This entire frame could be made from a variety or combination of materials, the only requirement being that it needs to hold the potentiometer in place axially to where the pen rotates.

B. System Characterisation

As a result of how the Adafruit DRV8871 works, two pulse with modulation (PWM) signals are given to the DC motor driver, Input 1 on the board is set low and Input 2 provides a PWM signal to indicate the speed (the current) given to the motor, vice versa for driving the opposite direction. These input signals range from 0 to 255. To characterise the internal friction of the system the drive signal was incremented from 0 until a potentiometer position change of greater than 5 occurred. This was used to determine the minimal drive current needed to overcome internal friction of the system. For the tested system this number was: 150. Tests were then conducted to determine the speed of the servo so a relationship between the input current and output rate could be determined. Code was developed to drive the servo towards a potentiometer position of 0 and to time the process, from its starting position to 0. The potentiometer had a range of motion of 180° . Before the code would run, the servo was manually placed 180° from the 0 position. The code displayed the starting position and the time it took the servo to get to 0. Three trials for each input signal were conducted and their average starting position and time calculated. It was assumed that all of the trials made a full 1π rotation. This gave a relationship of 0.0829, this proportionality will be denoted by κ . If ω represents the rate of the servo, θ the position, and u_1 the input signal. This is represented according to Eq. 1. Fig. 3 provides a plot of ω against u_1 .

$$\omega = 0.0829 \times u_1 - 13.19 \quad (1)$$

C. Control Loop

The LaPlace block diagram of the system, Fig. 4, was represented and a transfer function determined. This was used

to tune a PID controller for the servo where an input signal is given and a desired θ is reached. The controller was tuned to determine appropriate gains, and tweaked to get the desired transient behaviour. The tuned block response is shown in Fig. 5.

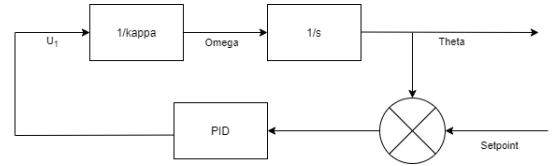


Fig. 4. LaPlace block diagram of the system.

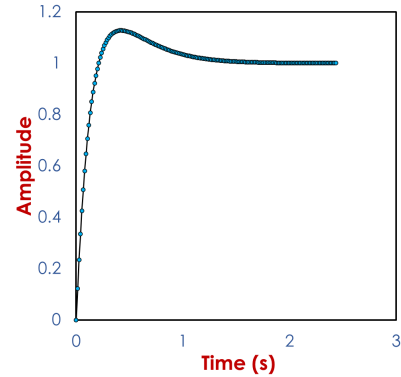


Fig. 5. Tuned block response.

D. Control System verification

To verify the tuning of the system, the servo was started in its two extreme positions, by stepping up from $0-90^\circ$ and stepping down from $180-90^\circ$. A layer of abstraction was added to the input so that an input angle(in degrees) could be given; the code then internally converts to the potentiometer's scale of values. The servo was connected to the flexible end effector. This means that the servo experienced a hindering load when

stepping down, and a helping load when stepping up, both of which can be treated as disturbances to the control loop. Both plots (Figs. 6 and 7) indicate a desirable response from the servo, and it handles going from set point to set point with similar transient behaviour, and minimal overshoot, like that expected of an off the shelf servo.

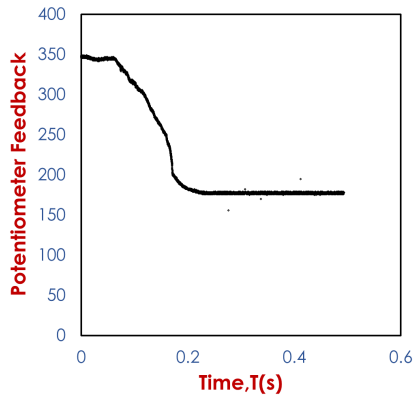


Fig. 6. Step down response for a 90 degree rotation.

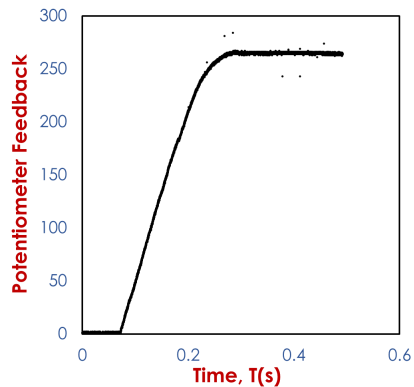


Fig. 7. Step up response for a 90 degree rotation.

Finally, the flexible end effector can be seen to move according to the active control system developed for this e-waste case study, Fig. 8.

III. IMPRACTICALITIES AND CHALLENGES IN E-WASTE UPCYCLING

Throughout the investigation of various e waste implementations, some things are clearly impractical to re-create from e-waste, and in some cases the cons out weigh the pros. An iMac G4 investigated consumes more power for less compute than an off the shelf Raspberry Pi. In this case, there may be a negative environmental impact as the processor of this device is significantly less efficient than modern processors. Finding ways to access the processor of cellphones or other smaller multi-thread processors may be a more viable and accessible solution. Some off the shelf items might be necessary to have

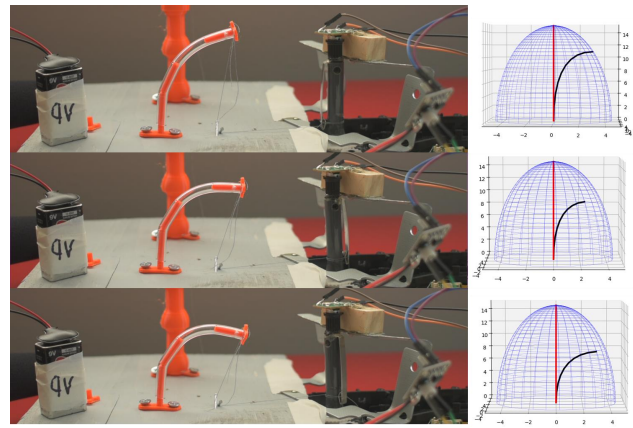


Fig. 8. Active control response system developed for the flexible end effector.

the tooling to further what is explored in this article. Things like: Flash chip programmers, JTAG/SWD debuggers, and logic analysers would all be very useful in reverse engineering e-waste. It may be possible to create these tools with e-waste at a significant time investment, but if the number of off the shelf components can be reduced to re-usable tools this would be an improvement to the current infrastructure and culture surrounding e-waste.

IV. CONCLUSIONS

This feasibility study has shown us that many components in discarded e-waste are perfectly functional and can be reused in alternative technologies, with more investigation into the development of e-waste robotics the potential for sustainable robotics research in LMICs could serve as a driving force for the strengthening of upcycled technologies.

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