Deep Learning-Enabled Robotic Disassembly for Sustainable E-Waste Recycling

Integrating AI and Robotics for Efficient E-Waste Management

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***Abstract*— Electronic waste is increasing at a pace that exceeds current recycling capabilities. Most recycling facilities still rely on slow, hazardous manual labor or rigid robotic systems limited to specific device types. This study presents a deep learning–enabled robotic disassembly framework that integrates real-time object detection using YOLOv5 and semantic segmentation using U-Net with a modular robotic arm capable of dynamic tool switching.**

A balanced dataset of twelve thousand four hundred fifty annotated images covering six device types and nine component categories was developed and evaluated using five-fold cross-validation to ensure robustness. The integrated system achieved a mean average precision of ninety-four point six percent for detection and a disassembly success rate of ninety-two point three percent, processing devices forty percent faster than manual operations.

When tested on one hundred fifty mixed e-waste devices, the system consistently maintained ninety-six point one percent material purity, outperforming both rule-based robotic systems and detection-only baselines. By merging computer vision intelligence with adaptive robotic mechanics, this work demonstrates a scalable path toward faster, safer, and more sustainable electronic waste recycling.

Keywords— deep learning; robotic disassembly; e-waste recycling; object detection; semantic segmentation; YOLOv5;

I. INTRODUCTION

The e-waste crisis is escalating at an alarming pace. According to the United Nations, more than **53.6 million metric tons** of electronic waste were generated in 2019, and projections indicate a **twenty-one percent** increase by 2030. Much of this waste contains valuable recoverable materials such as **gold, copper, palladium,** and **rare earth metals**, yet unsafe manual disassembly continues to dominate the recycling chain—often occurring in under-regulated environments with significant human health risks.

While brand-specific automated robots such as **Daisy** and **Liam** have demonstrated exceptional throughput for predefined device types, they remain impractical for real-world recycling centers, where **heterogeneity** is the norm. Devices vary in **size, design, screw placements, casing materials,** and **internal layouts**, even within the same brand over time.

The central challenge is the lack of a **flexible and intelligent system** that combines:

1. Real-time computer vision adaptable to any device geometry;
2. Precise mechanical tooling with built-in damage prevention; and
3. Multi-device adaptability in uncontrolled, mixed waste environments.

The **objective** of this work is to design and implement a **deep learning–powered robotic system** capable of automatically identifying, segmenting, and disassembling electronic waste across multiple brands and device categories. The focus is on **maximizing material recovery**, **reducing hazardous human exposure**, and **enabling scalable circular economy practices**.

Our research addresses this gap by developing a **brand-agnostic, modular robotic system** that integrates **real-time computer vision** with **adaptive mechanical actuation**, capable of operating directly on mixed e-waste streams **without prior sorting**.

II. .EASE OF USE

A. *System Setup and Configuration*

The proposed system is designed for rapid deployment and minimal calibration effort. Once powered, the robotic arm and vision module automatically initialize and synchronize through a pre-configured control interface. The operator simply places an electronic device on the platform, selects the device type from the menu, and starts the disassembly sequence. The system’s modular architecture ensures that new device categories can be added by uploading trained detection and segmentation weights, requiring no manual code modification.

B. *Maintenance and Scalability*

Ease of maintenance was prioritized to ensure consistent performance in industrial and academic environments. Each mechanical and vision module can be independently replaced or upgraded without disrupting the overall system. Additionally, the software framework supports plug-and-play integration of new models or tools, making the platform scalable for future device types and expanding datasets. These features together make the system user-friendly, adaptable, and sustainable for long-term operation.

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