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A DUAL-CONTROLLER EDGE INTELLIGENCE FRAMEWORK FOR SOLAR-POWERED AUTOMATED ELECTRONIC WASTE SORTING

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Abstract: Electronic waste (e-waste) has emerged as one of the fastest-growing waste streams worldwide, creating significant environmental and public health concerns due to the presence of hazardous materials and improper disposal practices. This paper presents a Dual-Controller Edge Intelligence Framework for Solar-Powered Automated Electronic Waste Sorting, designed to enhance recycling efficiency through intelligent classification and autonomous segregation. The proposed system integrates an ESP32-CAM module for image acquisition and machine learning based object recognition, while an Arduino controller manages sorting operations through a stepper motor mechanism. Classified e-waste categories are transmitted using a UART communication protocol, enabling accurate and coordinated actuation. A solar energy subsystem comprising a photovoltaic panel, battery, and charging circuit provides sustainable off-grid operation and reduces dependence on conventional power sources. Real-time system status is displayed through an LCD interface for improved monitoring and usability. Experimental evaluation demonstrates reliable communication, efficient sorting performance, and an overall classification accuracy of 88.9% across multiple e-waste categories. The framework offers a cost-effective, scalable, and environmentally responsible solution for automated electronic waste management applications.

Index Terms –Electronic Waste Sorting, Edge Intelligence, ESP32-CAM, Arduino, Machine Learning, Solar Energy, UART Communication, Sustainable Automation, Embedded Systems, Smart Recycling

I. Introduction

Rapid technological advancement and the widespread adoption of electronic devices have significantly improved modern lifestyles, communication systems, industrial operations, and digital connectivity. The continuous production of smartphones, computers, household appliances, and consumer electronics has accelerated replacement cycles, leading to a substantial increase in discarded electronic products. As electronic consumption continues to rise globally, effective management of obsolete devices has become a critical challenge for environmental sustainability and resource conservation. Among the various waste streams generated today, electronic waste, commonly known as e-waste, represents one of the fastest-growing categories due to the increasing demand for advanced technologies and frequent device upgrades.Improper disposal of e-waste releases hazardous substances such as lead, mercury, cadmium, and brominated compounds into soil, water, and air, causing severe environmental pollution and health risks. Conventional sorting methods primarily depend on manual labor, resulting in low efficiency, inconsistent classification, increased operational costs, and exposure of workers to toxic materials. These limitations highlight the necessity for intelligent and automated sorting systems capable of improving recycling accuracy while reducing human intervention. Recent developments in embedded systems, machine learning, computer vision, and renewable energy technologies have enabled the development of compact and cost-effective solutions for waste management applications.This project presents a Dual-Controller Edge Intelligence Framework for Solar-Powered Automated Electronic Waste Sorting. The proposed system combines machine learning based image classification with automated mechanical segregation to streamline the sorting process. An ESP32-CAM module captures images of electronic waste items and performs edge-level classification, while an Arduino controller manages motor actuation and sorting operations. Communication between the controllers is established through a UART serial interface, enabling reliable data exchange and coordinated system functionality. A stepper motor driven mechanism directs classified items into designated collection bins according to their category.To promote sustainable operation, the framework incorporates a solar energy subsystem consisting of a photovoltaic panel, battery storage unit, and charging circuit. This arrangement enables autonomous off-grid functionality while reducing dependence on conventional electrical power sources. Real-time status information is displayed through an LCD module, enhancing system transparency and usability. By integrating edge intelligence, embedded control, and renewable energy technologies, the proposed framework offers an efficient, economical, and environmentally responsible approach for automated electronic waste segregation and recycling applications in educational institutions, recycling centers, and community-level waste management facilities.

II. Related Works

Article[1] "TensorFlow Lite Micro: Embedded Machine Learning on TinyML Systems" by Robert David, Jared Duke, Advait Jain, and Vijay Janapa Reddi in 2021: This paper presents TensorFlow Lite Micro, a lightweight machine learning framework designed for microcontrollers and embedded devices. The framework enables neural network inference on hardware with limited memory and computational capabilities. Static memory allocation techniques are employed to improve efficiency and reliability. The study demonstrates the deployment of image classification and object detection models on low-power processors. Experimental results show that TinyML can provide real-time inference without cloud connectivity. The framework supports edge intelligence applications requiring low latency and energy consumption. Memory optimization strategies significantly reduce hardware requirements. The work serves as an important foundation for ESP32-CAM based machine learning applications and embedded vision systems.

Article[2] "A Review of Deep Learning Models for Waste Classification" by Muhammad Ali Khan, Muhammad Sharif, and Tanzila Saba in 2022: This study reviews deep learning architectures used in automated waste classification systems. Various convolutional neural networks including ResNet, MobileNet, and EfficientNet are evaluated. The authors discuss dataset preparation and image preprocessing techniques. Experimental comparisons reveal that transfer learning improves classification performance. The review highlights challenges associated with limited training data and environmental variations. Automated waste classification significantly improves recycling efficiency. Deep learning models demonstrate higher accuracy than conventional machine learning methods. The paper provides valuable insights for intelligent waste sorting applications.

Article[3] "EWasteNet: A Two-Stream Data Efficient Image Transformer Approach for E-Waste Classification" by Niful Islam, Md. Mehedi Hasan Jony, Emam Hasan, and Sunny Sutradhar in 2023: This paper introduces a transformer-based architecture specifically developed for e-waste image classification. The model combines visual feature extraction with attention mechanisms for improved recognition. A dedicated e-waste dataset is utilized to evaluate performance. Experimental results demonstrate high classification accuracy across multiple electronic waste categories. The architecture effectively handles variations in lighting and object orientation. Multi-scale feature learning enhances recognition capability. The proposed method outperforms several conventional CNN models. The research confirms the effectiveness of transformer networks in e-waste management applications.

Article[4] "Smart E-Waste Management System Utilizing Internet of Things and Deep Learning Approaches" by David Voskergian, Hovhannes Asatryan, and Armen Khachatryan in 2023: This study presents an intelligent e-waste management framework integrating IoT and deep learning technologies. Smart sensors collect waste information and transmit data for analysis. Deep learning models classify electronic waste items automatically. The system supports real-time monitoring and management of recycling processes. Experimental evaluation demonstrates reliable detection accuracy. Cloud-based connectivity enables remote supervision of waste collection facilities. The framework reduces manual intervention and operational costs. The proposed approach contributes to sustainable electronic waste management.

Article[5] "A Deep Learning-Based Approach to Segregate Solid Waste" by S. Sundaralingam, M. Pratheepan, and K. Rajesh in 2023: This research develops a computer vision system for automated waste segregation. Deep learning algorithms classify waste into predefined categories using image analysis. Data augmentation techniques improve model robustness. Experimental results show strong classification performance under different environmental conditions. The framework reduces dependency on manual sorting operations. Feature extraction mechanisms enhance recognition accuracy. Automated segregation improves recycling efficiency and resource recovery. The study demonstrates the practical applicability of AI in waste management.

Article[6] "Hybrid Deep Learning Model for Accurate Classification of Waste Generation and Recycling Materials" by Hongwei Zhang, Yufeng Liu, and Xiaohui Wang in 2023: This paper proposes a hybrid deep learning framework for waste classification. Multiple neural network models are combined to improve prediction accuracy. The system effectively distinguishes recyclable and non-recyclable materials. Extensive experiments validate the robustness of the proposed architecture. Advanced feature extraction techniques enhance classification performance. The hybrid approach demonstrates superior results compared to individual models. Automated waste recognition supports sustainable recycling operations. The study highlights the benefits of integrating multiple learning mechanisms.

Article[7] "Smart Waste Management: A Paradigm Shift Enabled by Artificial Intelligence" by Damilola B. Olawade, Chukwudi O. Nwankwo, and Emmanuel A. Ajayi in 2024: This review investigates the role of artificial intelligence in modern waste management systems. Applications including waste collection, monitoring, classification, and recycling are discussed. AI technologies improve operational efficiency and decision-making processes. The study examines challenges associated with implementation and scalability. Intelligent sorting systems demonstrate significant performance improvements. Sustainability benefits are highlighted throughout the review. Future research opportunities in AI-driven recycling are identified. The findings emphasize the importance of automation for environmental protection.

Article[8] "Wireless Sensor Network-Based Machine Learning Framework for Smart Waste Collection and Sorting" by Kiran Belsare, Anjali Patil, and Rohit Deshmukh in 2024: This study integrates wireless sensor networks with machine learning for intelligent waste management. Real-time monitoring capabilities improve collection and sorting efficiency. Sensor data are analyzed to support adaptive decision-making. The framework optimizes waste handling operations in urban environments. Experimental testing confirms reliable communication performance.

Article[9] "Classification of Recyclable Waste Using Deep Learning Techniques" by Ahmed Alharbi, Mohammed Alotaibi, and Fahad Alshammari in 2024: This paper evaluates deep learning models for recyclable waste classification. YOLO-based object detection architectures are analyzed and compared. Experimental results demonstrate strong recognition performance across multiple waste categories. Automated classification improves recycling accuracy and processing speed. The study examines detection performance under varying environmental conditions.

Article[10] "Optimizing Waste Sorting for Sustainability: An AI-Powered Automated Sorting Robot" by Tianyu Cheng, Wenbo Li, and Jianhua Zhang in 2024: This research introduces an intelligent robotic platform for automated waste sorting. Computer vision algorithms identify recyclable materials in real time. Robotic actuators perform precise sorting operations based on classification results. Experimental analysis demonstrates improved throughput and sorting accuracy.

Article[11] "An Automated Waste Classification System Using Deep Learning" by Md. Nahiduzzaman, Abdullah Al Mamun, and Samiul Islam in 2025: This paper presents a deep learning framework for automated waste classification. A comprehensive dataset containing multiple waste categories is utilized. Advanced neural networks improve classification reliability and robustness. Data augmentation techniques enhance model generalization performance. Experimental results demonstrate high recognition accuracy. The framework supports efficient recycling and waste processing operations.

Article[12] "Intelligent Waste Sorting for Urban Sustainability Using Deep Learning" by Ghulam Ahmad, Muhammad Bilal, and Syed Hassan Raza in 2025: This study develops a CNN-based intelligent waste segregation system. Multiple waste categories including plastic, metal, paper, and glass are automatically identified. Feature extraction and classification modules operate collaboratively to improve accuracy. Experimental testing demonstrates reliable sorting performance. The framework reduces dependence on manual segregation processes.

III. PROBLEM STETEMENT

The rapid increase in electronic device consumption has resulted in a significant rise in electronic waste generation worldwide. Conventional e-waste sorting methods rely heavily on manual labor, making the process slow, inefficient, costly, and potentially hazardous due to exposure to toxic substances such as lead, mercury, and cadmium. Many recycling facilities lack intelligent systems capable of accurately identifying and segregating different categories of electronic waste. Additionally, dependence on grid electricity limits deployment in remote and resource-constrained areas. The absence of an automated, energy-efficient, and cost-effective sorting mechanism creates challenges in achieving sustainable recycling, resource recovery, environmental protection, and effective management of growing electronic waste streams.

IV. OBJECTIVES

The primary objective of this study is to develop a solar-powered automated electronic waste sorting system capable of improving recycling efficiency through intelligent classification and segregation. The project aims to utilize an ESP32-CAM module with machine learning techniques for accurate identification of various e-waste categories. Another objective is to establish reliable communication between the ESP32-CAM and Arduino using a dual-controller architecture for coordinated operation. The study also focuses on implementing a stepper motor based sorting mechanism, reducing manual intervention, promoting sustainable off-grid operation through solar energy utilization, and enhancing environmental protection through efficient electronic waste management and resource recovery practices.

V. METHODOLOGY

1. Data Collection and Dataset Preparation: The methodology begins with collecting images of various electronic waste items such as printed circuit boards, batteries, cables, IC chips, capacitors, and other electronic components. Images are captured under different lighting conditions, orientations, and backgrounds to improve model robustness. The collected data are organized into separate classes according to the type of e-waste. A balanced dataset is maintained to ensure reliable training and accurate classification performance across all categories.

2)Data Preprocessing and Augmentation: The collected images undergo preprocessing to improve quality and consistency before model training. Image resizing, normalization, and noise reduction techniques are applied to standardize the dataset. Data augmentation methods such as rotation, flipping, brightness adjustment, and scaling are performed to increase dataset diversity. These operations help reduce overfitting and improve the model's ability to recognize e-waste items in real-world conditions.

3)Machine Learning Model Training: A lightweight machine learning model based on MobileNetV2 is trained using the prepared dataset. Transfer learning techniques are utilized to improve classification accuracy while reducing training time. The model learns visual features such as shape, texture, and color patterns associated with different electronic waste categories. After training, the model is converted into TensorFlow Lite format to enable efficient deployment on resource-constrained embedded hardware.

4)ESP32-CAM Based Image Classification: The ESP32-CAM module captures real-time images of electronic waste items placed in the sorting area. The captured images are preprocessed and supplied to the trained TensorFlow Lite model for inference. Based on the prediction results, the system determines the appropriate waste category with the highest confidence score. This edge intelligence approach enables local processing without requiring cloud connectivity, reducing latency and improving system responsiveness.

5)Dual-Controller Communication Framework:A dual-controller architecture is implemented using the ESP32-CAM and Arduino microcontrollers. The ESP32-CAM performs image acquisition and machine learning inference, while the Arduino manages sorting operations and peripheral control. Classification results are transmitted through UART serial communication at a predefined baud rate. This separation of responsibilities improves system reliability, simplifies debugging, and enhances overall operational efficiency.

6)Automated Sorting and Actuation Mechanism: Upon receiving the classification label, the Arduino maps the detected category to a predefined bin location. A stepper motor driver generates control signals that rotate the sorting mechanism toward the corresponding collection bin. The motor provides accurate positioning to ensure proper segregation of electronic waste items. After depositing the item, the mechanism returns to its initial position and prepares for the next sorting cycle.

7) Solar Power Management and System Monitoring: The entire system is powered using a solar energy subsystem consisting of a photovoltaic panel, battery, charging circuit, and voltage regulation modules. Solar energy is stored in the battery and utilized to operate the controllers, sensors, display, and motor. A 16×2 LCD continuously displays classification results and system status information. This renewable energy approach supports sustainable operation, reduces electricity consumption, and enables deployment in locations with limited access to conventional power sources.

VI. SYSTEM ARCHITECTURE

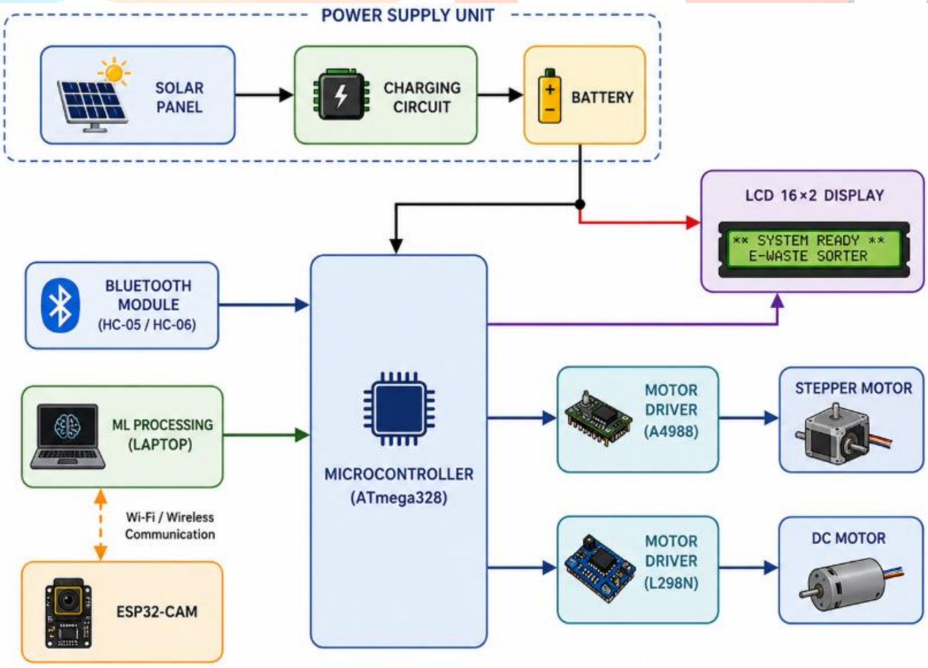

Fig 1: System Architecture of the Dual-Controller Edge Intelligence Framework for Solar-Powered Automated Electronic Waste Sorting

The system architecture of the proposed Dual-Controller Edge Intelligence Framework for Solar-Powered Automated Electronic Waste Sorting is designed to enable intelligent classification and automated segregation of electronic waste. The power supply unit consists of a solar panel, charging circuit, and rechargeable battery, which provide sustainable energy for the entire system. An ESP32-CAM module captures images of electronic waste items and transmits them to a laptop-based machine learning processing unit for classification. The classification results are communicated to the ATmega328 microcontroller through wireless communication and a Bluetooth module. Acting as the central controller, the ATmega328 processes the received data and coordinates all system operations. Based on the identified waste category, control signals are sent to motor driver modules that operate a stepper motor and DC motor for accurate sorting and movement mechanisms. Simultaneously, a 16×2 LCD display provides real-time information regarding system status and detected waste categories. This integrated architecture combines renewable energy, machine learning, wireless communication, and automated actuation to achieve efficient, reliable, and environmentally sustainable electronic waste sorting.

VII. EXPERIMENTAL SETUP

Fig. 2: Prototype Implementation of the Solar-Powered Automated Electronic Waste Sorting System

The figure shows the developed hardware prototype consisting of a solar panel, sorting bins, Arduino-based control unit, LCD display, and supporting electronic components.

VIII. CONCLUSION AND FUTURE WORKS

In this research, a Dual-Controller Edge Intelligence Framework for Solar-Powered Automated Electronic Waste Sorting was successfully developed to improve recycling efficiency and reduce manual intervention. The system combined machine learning based classification, embedded control, wireless communication, and renewable energy to achieve accurate and sustainable e-waste segregation. Experimental results demonstrated reliable operation, effective sorting performance, and practical applicability for waste management environments. Future work may focus on expanding waste categories, integrating advanced deep learning models, implementing cloud connectivity, enhancing sorting speed, and developing robotic pick-and-place mechanisms. Additional optimization of power management and edge intelligence can further improve scalability and deployment capabilities.

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