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Design and Development of an IoT-Driven Land Cleaning Robot

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Abstract: Improper disposal of electronic waste (E-waste) and medical waste creates environmental and safety concerns because these materials may contain hazardous electronic components, sharp objects or potentially contaminated items. Manual collection and segregation can expose sanitation workers to these risks and may lead to incorrect disposal. This paper presents the design and development of an IoT-driven autonomous mobile robot intended to identify, approach, collect and segregate E-waste and medical waste. The prototype combines embedded computing, computer vision, mobile robotics and wireless communication in a compact platform. A Raspberry Pi 4 Model B acts as the main processing unit, while a Raspberry Pi Camera Module V2 captures images of waste objects. OpenCV is used for image preprocessing, including HSV colour-space segmentation and morphological filtering. A lightweight MobileNetV2-SSD object detector, executed using TensorFlow Lite, classifies the detected object and estimates its position. A proportional-derivative visual tracking controller uses the object's image position to guide the differential-drive robot. An L298N motor driver controls the DC geared motors, and an HC-SR04 ultrasonic sensor measures the distance to the target and provides a stopping condition at approximately 12 cm. For segregation, an SG90 servo positions the diverter flap and an MG996R servo operates the pusher mechanism. The system routes E-waste and medical waste into separate onboard containers. An OLED display and piezo buzzer provide local status information, while an ESP8266/ESP-01 module supports wireless telemetry. The project report records testing with 250 samples across five categories, with a precision of 94.3%, recall of 92.4% and F1-score of 93.3%. It also reports an average processing time of 54 ms per frame and an average segregation rate of 91.4%. These reported results indicate that edge-based vision and a mobile sorting mechanism can be integrated for localized waste collection under controlled conditions. Further validation is required under different lighting, floor and waste conditions before practical deployment.

Keywords: IoT, E-waste, medical waste, autonomous robot, computer vision, Raspberry Pi, waste segregation.

I. INTRODUCTION

Growth in electronic-device use and healthcare services has increased the quantity of discarded electronic and medical materials. E-waste includes printed circuit boards, batteries, connectors and electronic components, while medical waste may include used masks, gloves, medicine packaging and sharp or contaminated materials. Improper disposal can create risks for workers and the environment [11], [12]. Conventional collection often depends on manual handling. Fixed conveyor-based sorting systems can automate some operations, but they are generally stationary and may require waste to be fed into the machine. A mobile robot that detects waste, moves towards it and separates it into designated containers can support safer and more organized collection. The proposed system combines camera-based recognition, autonomous movement, distance sensing, mechanical segregation and IoT-based status reporting in one platform.

II. LITERATURE REVIEW

Research on automated waste management has explored machine-learning-based classification and robotic collection. Kumar et al. discuss artificial-intelligence-based waste separation [1], while Rahman and Al-Mamun describe a vision-based mobile trash-collection robot using deep convolutional networks [2]. Zhang et al. investigate real-time detection of hazardous biomedical waste using a lightweight YOLO model [3]. Puri and Nayak study visual servoing for handling electronic scrap [4], and Santhosh and Vijayalakshmi discuss IoT-enabled segregation of hospital bio-waste [5]. MobileNet models support efficient vision processing on resource-constrained devices [7], while YOLO provides a real-time object-detection approach [6]. These studies provide a basis for combining object recognition, robot movement and waste handling in the proposed prototype.

III. METHODOLOGY

The robot follows a scan–detect–track–approach–segregate cycle. First, the Raspberry Pi Camera Module V2 captures the area in front of the robot. OpenCV preprocesses the frames using HSV colour conversion, segmentation and

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morphological operations. The MobileNetV2-SSD model running through TensorFlow Lite identifies the object class and its image location. The software maps the recognized class to either the E-waste or medical-waste category.

After detection, the centre of the object's bounding box is compared with the centre of the camera frame. The resulting horizontal error is supplied to a proportional-derivative controller, which adjusts the left and right motor speeds. The L298N driver controls the direction and speed of the DC geared motors [10]. During approach, the HC-SR04 ultrasonic sensor measures the distance to the target. When the distance reaches approximately 12 cm, the robot stops.

The SG90 servo positions the diverter flap according to the selected category: the project report specifies 45° for the E-waste route and 135° for the medical-waste route. The MG996R servo moves the pusher arm to transfer the item into the selected container, then retracts. Tub A is assigned to E-waste and Tub B to medical waste. The OLED display and buzzer indicate the operating state, while the ESP8266/ESP-01 module receives status data from the Raspberry Pi through UART and transmits it over Wi-Fi [8]. The system then returns to scanning for the next item.

IV. HARDWARE AND SOFTWARE REQUIREMENTS AND DESIGN

The hardware and software elements used in the prototype are summarized in Table 1. The Raspberry Pi 4 is the main controller and executes image processing, object detection and navigation. The power unit uses a 3S 18650 lithium-ion battery pack and an LM2596 buck converter to provide regulated power. The Raspberry Pi platform and motor driver are described in their respective product documentation [9], [10].

TABLE I HARDWARE AND SOFTWARE REQUIREMENTS

Category	Requirement	Function / Use
Controller	Raspberry Pi 4 Model B (4 GB)	Main processing and robot control
Vision	Raspberry Pi Camera Module V2	Captures images of waste objects
Drive system	L298N, DC geared motors, chassis and wheels	Controls robot movement
Sensors	HC-SR04 ultrasonic sensor	Measures target distance; stop at about 12 cm
Segregation	MG996R and SG90 servo motors	Pusher and category-selecting diverter
Feedback / IoT	SSD1306 OLED, buzzer, ESP8266/ESP-01	Status display, sound alert and Wi-Fi telemetry
Power	3S 18650 battery, LM2596 buck converter	Portable and regulated power supply
Software	Python, OpenCV, TensorFlow Lite	Image processing and object detection
Communication	UART and Wi-Fi	Transfers system status to the IoT module

The software design is divided into camera acquisition, image preprocessing, object detection, category decision, navigation, motor control, servo actuation and telemetry modules. The navigation module calculates target-position error and generates motor commands. The segregation module selects the diverter angle and operates the pusher. A state-based sequence coordinates the modules: SCAN → DETECT → TRACK → APPROACH → STOP → SELECT ROUTE → PUSH → REPORT. Error or obstacle conditions place the robot in a stopped state.

V. EXPECTED OUTCOME

The expected outcome is a mobile prototype that can recognize E-waste and medical-waste objects, approach a selected target and transfer it into the correct onboard container. It is intended to reduce direct manual handling, provide local operating feedback and support remote status monitoring through Wi-Fi. Table 2 summarizes the reported prototype measurements. The figures are taken from the project report's results section and should be checked against the original test records before publication.

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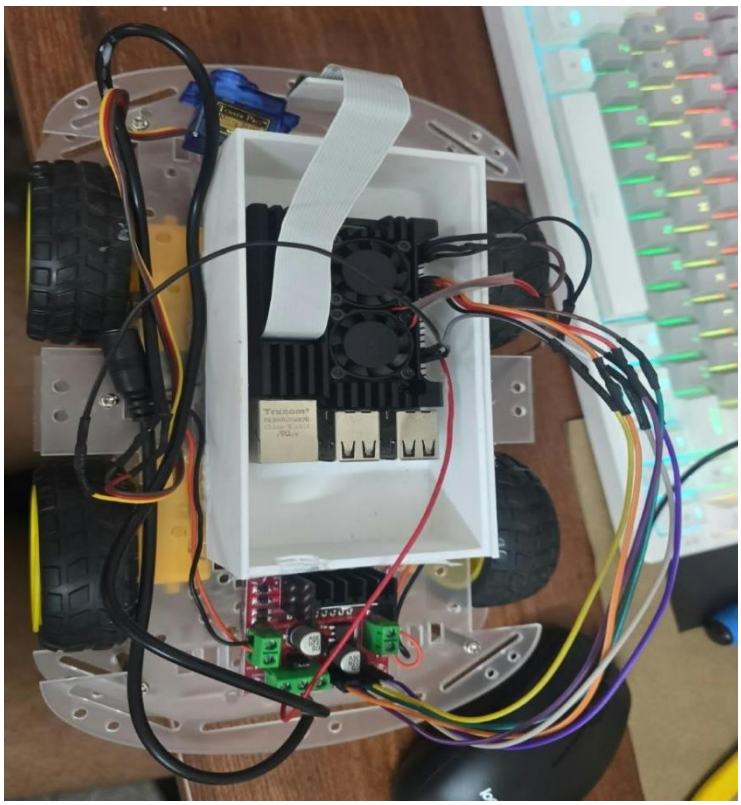
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TABLE II REPORTED PROTOTYPE PERFORMANCE

Parameter	Reported value
Test samples	250 samples across five categories
Detection precision	94.3%
Detection recall	92.4%
F1-score	93.3%
Processing latency	54 ms/frame (about 18.5 FPS)
Average chute segregation rate	91.4%
Average sorting cycle	4.68 seconds per item

Performance may be affected by lighting changes, reflective packaging, flexible objects, occlusion and differences in object size. Additional testing in varied indoor and outdoor conditions is needed to assess reliability and practical use.



VI. CONCLUSION

This paper presents an IoT-driven autonomous mobile robot for detecting, collecting and segregating E-waste and medical waste. The design integrates Raspberry Pi-based computer vision, visual tracking, ultrasonic distance measurement, differential-drive movement and a servo-operated sorting mechanism. Wireless telemetry and local indicators provide system-status information. The measurements reported in the project indicate the feasibility of combining edge-based recognition with mobile waste segregation in a controlled environment. Future improvements should focus on testing with more varied waste samples, improving collection of irregular objects and validating the robot in real operating conditions. Appropriate containment and safe handling procedures remain necessary, particularly for medical waste.

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