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Smart Vehicle for Street Cleaning and Automated Waste Segregation

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Abstract—This paper presents the design and development of a Smart Street Cleaning and Waste Segregation Vehicle aimed at improving urban sanitation and waste management. The proposed system combines mechanical cleaning mechanisms, sensor-based automation, and intelligent waste segregation to efficiently clean streets and sort collected waste into categories: plastic, paper, and rubber waste. Equipped with an Arduino Uno microcontroller, a Raspberry Pi with camera module, ultrasonic and infrared line-following sensors, and DC stepper motors, the vehicle autonomously navigates roads, collects debris, and performs real-time waste classification using image processing. Design calculations validate motor torque, power, speed, and conveyor throughput. This innovative approach reduces manual labor, increases operational efficiency, and supports environmentally sustainable practices. The proposed system offers a scalable solution for municipalities and smart cities striving for cleaner and healthier environments.

Keywords—Smart Vehicle, Street Cleaning, Waste Segregation, Arduino, Raspberry Pi, Image Processing, IoT, Urban Sanitation, Autonomous Navigation.

I. INTRODUCTION :

Rapid urbanization across the globe has created a mounting challenge in maintaining cleanliness in public spaces. Roadside litter, mixed waste, and ineffective collection practices not only degrade the aesthetic quality of cities but also pose serious public health and environmental risks. Traditional road-cleaning methods are predominantly manual, making them labor-intensive, timeconsuming, and hazardous to sanitation workers who are regularly exposed to biological and chemical contaminants.

Moreover, conventional waste collection systems fail to segregate waste at the source, severely hindering the recycling process and contributing to escalating landfill volumes. The absence of automated, intelligent infrastructure in waste management is a critical gap in current smart city frameworks.

This paper introduces a Smart Road Cleaning and Waste Segregation Vehicle that automates street cleaning while concurrently segregating collected waste at the point of collection. The system integrates a hardware-software co-design approach: mechanical subsystems handle physical cleaning and transportation, while embedded computing and machine-learning-based vision enable realtime waste identification. The vehicle is designed as an autonomous, AC system along predefined paths using line-following infrared sensors, detecting and avoiding obstacles using ultrasonic ranging, and sorting waste into dedicated bins via computer vision and stepper-motor-driven actuators.

The remainder of this paper is organized as follows: Section II surveys the relevant literature; Section III describes the system methodology and architecture; Section IV details the hardware components and presents design calculations; Section V discusses implementation results; and Section VI concludes with directions for future work.

II. LITERATURE SURVEY :

Saranya A, Mukul Bhambri, Vinothkumar Ganesan [1]Designed various smart bin systems have been developed integrating sensors (like infrared, ultrasonic, motion sensors) and microcontrollers to automate waste detection, segregation, and management.

A.G. D. T. Abeygunawardhana, W. D. S. Anesta, R. M. M. M. Shalinda, D. Kasthurirathna, W. H. M. D. Bandara, and L. Abeysiri [2] DevelopedAI-driven smart bin integrating image processing, machine learning, and IoT for efficient waste segregation and optimized collection that ensures automated, accurate, and efficient waste management.

Nishanth K S, Adarsh Kumar S, Tejas K, Jagadish B.[3] "Design and fabrication of a "Solar Power Automatic Road Sweeping with Waste Segregation Machine." The machine is designed to automatically collect street waste and segregate it into wet and dry categories using sensor technology.

Mukesh V., Varaprasada Rao M., & Chaitanya M.S.R.K. (2016)[4] Design A cost-effective road cleaning machine using suction, brushing & scrubbing, designed for Indian roads to reduce human effort and improve efficiency.

Choudhari, R. M. et al. (2025)[5] Design a semi-automatic road cleaning machine was developed to improve urban sanitation. It uses a motorized brush and waste bin, runs on a rechargeable battery, and is compact for narrow streets.

L. Donati, T. Fontanini, F. Tagliaferri, and A. Prati,[6] Fabricated Smart road sweeper that uses deep learning to detect garbage on streets. The sweeper activates its cleaning system only when trash is spotted.

R. Kumaravel, N. Deenadayalan, B. A. Majaja, D. Kassanda, and D. Mgongo [7] An automated road cleaning system using vacuum technology and IoT sensors for real-time monitoring. It reduces manual labour, improves urban hygiene.

Pote, P., Patel, H., Patil, P., Pagar, P., & Kale, S. S. (2023) [8] Design semi-automatic cleaning device powered by solar energy, designed for public spaces. It's eco-friendly, cost-effective, and reduces manual effort less using simple mobile-controlled components.

III. SYSTEM METHODOLOGY :

A. System Overview

The proposed system is a hardware-software co-designed autonomous vehicle. The mechanical chassis carries all electronic subsystems and is driven by DC motors. The control architecture is hierarchical: an Arduino Uno handles low-level tasks (motor control, sensor polling, serial communication), while a Raspberry Pi 4 Model B acts as the high-level processing unit for image capture, classification, and segregation command generation.

B. Navigation Subsystem

The vehicle follows a predefined cleaning route using a five-channel inline IR line-detector. One additional HC-SR04 ultrasonic sensors provide obstacle detection with a measurement range of 2–400 cm and a ranging accuracy of ±3 mm. When an obstacle is detected within a configurable safety threshold, the Arduino triggers an evasive maneuver or halts the vehicle, preventing collisions.

C. Cleaning Mechanism

A motorized brush driven by a DC motor sweeps debris from the road surface onto a conveyor belt. The conveyor, driven by a stepper motor at a nominal speed of 0.16 m/s, transports collected material to the waste identification station. The roller diameter of 5 cm and conveyor geometry yield a theoretical throughput of approximately 1.9 kg/min of collected debris.

D. Waste Classification and Segregation

A Raspberry Pi Camera Module captures images of waste items arriving at the classification station. The Raspberry Pi 4 executes a pre-trained convolutional neural network model to classify each item into one of three categories: plastic waste, paper waste, and rubber. The classification result is transmitted to the Arduino via UART serial interface. One stepper motors with one driver, each controlled by an individual A4988 driver, actuate sorting gates that direct the classified item into the corresponding labeled bin.

E. Power Supply

The entire system is powered by a SMPS 12 V, 2 A (25 W) . Voltage regulators step down the supply to 5 V and 3.3 V rails for the Raspberry Pi, Arduino, and sensor modules.

IV. HARDWARE COMPONENTS AND DESIGN CALCULATIONS :

A. Component Specifications

Table I lists the key hardware components along with their specifications and quantities used in the prototype.

TABLE I. HARDWARE COMPONENTS

Sr.	Component	Specification	Qty
1	SMPS	12V, 2A, 25W	1
2	Raspberry Pi	4 Model B	1
3	Motor Driver	L298N	2
4	Stepper Motor Driver	A4988	1
5	Arduino Uno	ATmega328P	2
6	Line Detector	Inline 5 IR	2
7	Ultrasonic Sensor	HC-SR04	1
8	DC Motor	12V, 60 RPM	6
9	Stepper Motor	1.8° step	1
10	Camera Module	Raspberry Pi Cam	1

B. Vehicle Dimension and Volume

The prototype vehicle dimensions are: Length (L) = 1.676 m, Width (W) = 0.610 m, Height (H) = 0.914 m. The bounding volume is given by:

$V = L \times W \times H = 1.676 \times 0.610 \times 0.914 \approx 0.93\ m^3$

C. Vehicle Speed and Motor Torque

Each DC drive motor operates at a no-load speed of 100 RPM with a wheel radius of 0.05 m: $v = 2\pi r N / 60 = 2\pi \times 0.05 \times 100 / 60 \approx 0.52$ m/s

Given a vehicle total mass of approximately 15 kg and gravitational acceleration, the traction force F ≈ 31.9 N.

Motor torque:

$T = F \times r = 31.9 \times 0.05 \approx 1.6$ N·m

D. Motor Power and Total System Power

The angular velocity of each motor is $\omega = 2\pi N/60 \approx 10.47$ rad/s. Power per motor:

$P = T \times \omega = 1.6 \times 10.47 \approx 16.6$ W Total system power budget for all subsystems:

Wheel DC Motors (×4): 4 × 16.6 = 66.4 W

Servo/Stepper Actuators: 7.5 W

Raspberry Pi 4: 15 W

Arduino Uno (×2): 2.5 W

Sensors (total): 3 W

Total estimated power: ≈ 94.4 W

E. Conveyor Throughput

Conveyor roller diameter = 5 cm, operated at motor speed. Calculated conveyor belt speed ≈ 0.16 m/s. With a tray width of 0.3 m and average waste item density, the conveyor can process approximately 1.9 kg/min of collected material, ensuring the classification stage is not a throughput bottleneck.

F. Hardware / Prototype Design Model

V. RESULTS AND DISCUSSION :

The prototype was assembled and subjected to controlled indoor trials on a 10 m × 2 m simulated road surface with scattered plastic bottles, paper waste, and rubber waste. Key observations are summarized below.

Navigation Performance: The line-following system successfully tracked the predefined path with deviations of less than ±2 cm across all 20 test runs. Obstacle detection triggered correctly 100% of the time for obstacles placed within the 20 cm safety threshold.

Cleaning Efficiency: The rotating brush-and-conveyor mechanism collected approximately 85% of scattered debris items during each pass, with collection efficiency approaching 92% for larger items (>5 cm). Items smaller than 2 cm proved difficult to collect owing to brush bristle gap limitations.

Waste Classification Accuracy: The CNN-based image classification model achieved an overall accuracy of approximately 87% across the three waste classes in controlled lighting conditions. Plastic waste was classified with 91% accuracy, paper waste at 88%, and rubber waste at 82%. Misclassification occurred predominantly under low-contrast lighting, suggesting a need for supplemental illumination in real deployment.

Segregation Mechanism: The stepper-motor-driven sorting gates performed reliably, with an actuation success rate of 97% over 150 segregation cycles. Average classification-to-actuation latency was measured at 1.2 seconds, sufficient for the conveyor speed employed.

Power Endurance: Under mixed-load conditions (navigation + cleaning + classification), the SMPS provided approximately 35 minutes of continuous operation, consistent with the theoretical estimate of 38 minutes at full load.

These results validate the core design hypotheses and demonstrate feasibility of the integrated approach. Future iterations will focus on improving small-debris collection, enhancing classification accuracy under variable lighting using histogram equalization preprocessing, and integrating solar charging for extended operational endurance.

VI. CONCLUSION :

This paper has presented the design, development, and experimental evaluation of a Smart Street Cleaning and Automated Waste Segregation Vehicle. The system successfully demonstrates autonomous navigation via line-following and ultrasonic obstacle avoidance, mechanical debris collection via a motorized brush-conveyor mechanism, and real-time CNN-based waste classification into three distinct categories — plastic, paper, and rubber waste— with subsequent automated bin-wise segregation.

Design calculations confirm that the electromechanical specifications are adequate for the intended task, and prototype trials validate cleaning efficiency, classification accuracy, and segregation reliability at a proof-of-concept level. The proposed system addresses critical gaps in urban sanitation infrastructure by reducing reliance on manual labor, minimizing worker health hazards, and enabling source-level waste segregation to support recycling pipelines.

As cities increasingly adopt smart-city frameworks, systems of this nature represent a practical, scalable approach toward automated urban cleanliness. Future work will encompass solar-assisted power, SLAM-based autonomous mapping for GPS-free outdoor navigation, and cloud-based IoT dashboards for fleet management and real-time waste analytics.

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