Autonomous Urban Recycler (AURo)

Team AURoTech

Team Members

- **Garvit Singhal**
- **Krishiv Gupta**
- **Aryendra Singh Rathore**

Team Presentation

- I'm **Garvit Singhal**, a 15-year-old high-school student based in **Jaipur, India**. I have a deep passion for all areas of technology, especially anything that can benefit society through **IoT**, **AI**, and **Machine Learning**.
- My role in this project: **I developed the software & designed the LLM algorithm.**

- I'm **Krishiv Gupta**, a 15-year-old student in Class 10 at **Cambridge Court World School**. I'm a diligent learner, passionate about contributing to our project. I'm excited to collaborate with the team and committed to delivering quality work.
- My role in this project: **I created the hardware and navigation,& adjusted the software accordingly.**

- I'm **Aryendra Singh Rathore**, a 15-year-old aspiring student from **Cambridge Court World School** and a passionate **robotics enthusiast**. I'm eager to explore new horizons and make meaningful contributions through innovative projects.
- I am responsible for **PPT, Presentation, & Research work.**

Submitted on {TBD}.

1. Introduction:

● Project Overview:

This project presents an **automated four-wheel mobile robot** designed to enhance urban waste management. Equipped with a **4-axis robotic arm** and **six internal compartments,** the robot **autonomously services smart dustbins, collecting and segregating waste** using sensor and vision-based classification techniques.

● Problem Statement:

In Indian cities, **30–40%** of waste, approximately **18.6 to 24.8 million tons annually**, is either not collected or ends up scattered on streets due to:

- **Poor waste collection** systems
- **Irregular disposal practices**
- **Lack of public awareness**

Uncollected waste **clogs drains** and leads to **stagnant water**, which can cause serious public health issues such as **dengue, malaria, and cholera.**

● Solution:

The proposed solution uses an autonomous robotic system that:

- **Navigates urban environments**
- **Communicates with smart dustbins via ESP modules**
- Uses **Arduino Mega and ESP32-CAM for control and processing**
- Performs **real-time waste collection and sorting using vision and sensors**
- **Organises waste into six categorised compartments**

This system ensures source-level segregation and **automated pickup, significantly improving waste management efficiency.**

● Benefits:

- **Minimises manual labour and exposure to hazardous waste**
- Improves segregation accuracy, leading to **higher recycling rates**
- Helps **prevent disease outbreaks** by reducing street litter
- **Lowers operational costs** for municipalities over time
- Supports a **cleaner urban environment**

- ## Efficiency:

  The robot provides:

  - **Timely and consistent waste collection**
  - **Autonomous navigation and decision-making**
  - **Precise waste classification using advanced sensors and vision**
  - **Reliable communication between bins and the robot for optimized performance**

- ## Real-Life Application:

  Ideal for deployment in:

  - **Urban municipal zones**
  - **Smart city initiatives**
  - **Gated communities and residential complexes**
  - **Commercial and industrial campuses**

2. Robotic Solution Overview:

This project is a **completely self-sufficient, connected waste-separation system** aimed at optimising city refuse collection and recycling. Fitted with a **four-wheeled differential-drive chassis** and a **four-axis manipulator arm**, the robot utilises an **ESP32-CAM-mounted end effector** for **real-time visual identification** of single waste items, while **built-in ultrasonic sensors** enable **360° obstacle evasion**. Upon getting **"bin full" notifications** through **MQTT** from smart city trash bins (each equipped with an **ESP8266** and **ultrasonic level sensor**), the robot moves to the designated spot using **waypoint navigation** and **wheel-encoder–aided odometry**. It triggers the bin's **release system**, **vibrates its tray** to settle contents, and carries out a **multi-step sorting process**: **moisture detection** guides damp waste to the **wet waste section**; a **specialised metal detector** identifies metal objects; and a **lightweight vision algorithm** sorts **paper, glass, and plastics** into their designated bins, while any **unidentified items** are redirected to another compartment. All subsystems—**sensor integration**, **actuator management**, and **decision-making logic**—are coordinated by an **Arduino Mega**, while **advanced monitoring**, **diagnostics**, and **route planning** are supported through **cloud-based LLM APIs**, allowing for **natural-language updates** and **adaptable task scheduling**. This coordinated method not only **automates the complete waste-collection process** but also **generates detailed telemetry** for effective recycling operations.

3. Project Initiation:

- Define project objectives, scope, and deliverables.
- Establish project team roles and responsibilities.
- Set up project management tools and communication channels.

Research and Requirements Gathering:

- Conduct a comprehensive review of existing Waste collection and sorting technologies and systems.
- Gather requirements from stakeholders, including end-users, researchers, and emergency responders.
- Identify technical specifications and performance criteria for the robotic solution.

Conceptual Design:

- Develop conceptual design of the robotic solution, including:
- Overall architecture and system components.
- Sensor configurations and placement.
- Mobility and navigation mechanisms.
- Create conceptual drawings and schematics to visualise the design.

4. Hardware Development:

Procure or develop necessary hardware components, including:

Chassis & Mobility

- Four-wheeled differential-drive chassis frame
- 4 × DC geared motors
- 4 × Wheel encoders
- Motor driver shield L298N

Manipulation

- Four-axis manipulator arm servo-based
- High-torque servos
- Vibration motor

Sensing & Vision

- ESP32-CAM module (object recognition)
- 8 × Ultrasonic range sensors (for 360° obstacle detection)
- Ultrasonic level sensor (in each smart bin)
- Moisture sensor
- Metal detection module
- VL53L1X (Depth analysis)

Computation & Control

- Arduino Mega 2560 (central coordination)
- ESP8266 (MQTT gateway for smart bins)
- ESP32 Cam,(Navigation and LLM segmentation)

Power & Electrical

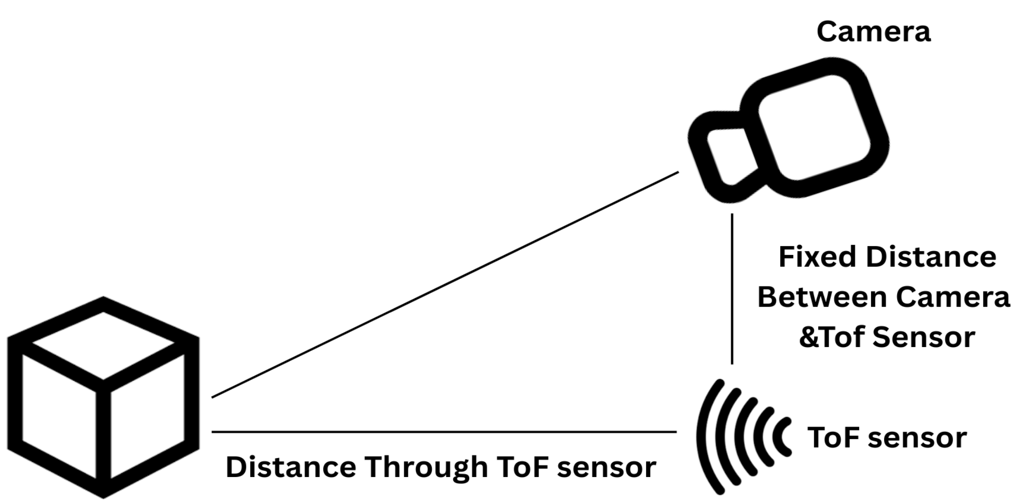
- Rechargeable Li-ion or $LiFePO_4$ battery pack
- DC–DC converters/voltage regulators

Communications

- Wi-Fi modules (ESP32/ESP8266)
- MQTT broker (cloud)

5. Software Development:

- Program a microcontroller for sensor data acquisition and processing.
- Develop code for image capture and transmission using the ESP32 Cam module.
- Create scripts for LLM to recognise trash and use a Single point ToF sensor and an Camera to calculate the angle to take the arm to the trash.



The camera and ToF sensor are mounted at a known fixed distance apart (say h), and the ToF sensor measures the distance d from the sensor to the trash object. Assuming a flat ground, we can compute the angle θ from the arm base to the trash using basic trigonometry:

$$\theta = tan^{-1}(h/d)$$

Where:

- θ is the angle between the arm and the trash object (in radians or degrees),
- h is the vertical or horizontal offset between the camera and the ToF sensor,
- d is the direct distance to the trash from the ToF sensor.

This angle is used to rotate the robotic arm to align with the trash for pickup

```
import math
h = 10  # Fixed Distance between ToF sensor and camera
d = get_distance_from_tof_sensor()
theta_rad = math.atan(h / d)
theta_deg = math.degrees(theta_rad)
print(f"Angle to trash: {theta_deg:.2f}°")
```

This approach combines AI-based vision for detection with geometric reasoning for precise robotic manipulation — all while using low-cost sensors.

- Make the Sorting algorithm using the sensors and ESP32-Cam
- Test software components individually and in conjunction with hardware.

Integration and Testing:

- Integrate hardware and software components to create a functional prototype of the robotic solution.
- Conduct rigorous testing to evaluate performance and reliability:
- Test sensor accuracy and responsiveness in simulated and real-world conditions.
- Assess data transmission and communication capabilities.
- Iterate on design and implementation based on test results and feedback.

Documentation and Training:

- Document the robotic solution's design specifications, technical details, and user manuals.
- Develop training materials and conduct training sessions for end-users and maintenance personnel.
- Ensure comprehensive documentation of the development process for future reference and knowledge transfer.

Deployment and Field Testing:

- Deploy the robotic solution in an actual City or a landfill.
- Monitor system performance and collect data on its effectiveness in clearing the area.
- Gather feedback from end-users and stakeholders to identify areas for improvement and optimisation.

6. Evaluation and Optimisation:

- Evaluate field test results and performance metrics against project objectives and requirements.
- Identify and address any issues or shortcomings through software updates, hardware modifications, or system enhancements.
- Based on feedback and lessons learned, optimise the robotic solution for improved accuracy, reliability, and usability.

Scaling and Expansion Plans :

- Explore opportunities for scaling and expanding the robotic solution to additional regions or applications.
- Consider potential partnerships or collaborations for further development and deployment.
- Continuously monitor advancements in technology and research for future enhancements and upgrades.

7. Design and Methodology of Mechanical Construction:

The mechanical construction of AURo integrates various sensors and components within a robust framework to ensure accurate monitoring of soil parameters and effective communication of warning alerts. Here's a breakdown of the design and methodology:

Structural Framework:

- The AURo system is built on a **rugged four-wheel mobile platform** designed to operate on **urban terrain**.
- It houses a **4-axis robotic arm** and **six internal compartments** for effective waste segregation. The chassis and enclosure are **durable and weather-resistant**, protecting onboard electronics from environmental exposure.
- The robot includes **mounting points** for sensors and cameras to ensure optimal data collection and object detection.

Sensor Integration:

- **ESP32-CAM** for **visual waste detection** and guidance of the robotic arm
- **Soil moisture sensor** to differentiate between **wet and dry waste**
- **Metal detection circuit** (open circuit) for identifying **metallic waste**
- **Ultrasonic sensors** (4 directions) for **obstacle avoidance** and **navigation**
- **ToF sensors** for proximity and alignment
- **Load cells** *(future integration)* to measure compartment capacity

Microcontroller and Data Processing:

- An **Arduino Mega** serves as the primary controller, coordinating the movement of the **4 servo motors** on the robotic arm, the **motor driver** for the wheels, and all sensor inputs.

- Data from the **ESP32-CAM**, **moisture sensor**, and **metal detector** is processed to guide the arm's actions. The robot uses **logic-based sequencing** to determine waste type and deposit it in the correct compartment.
- **Large Language Models (LLMs)** and **AI** assist in higher-level decision-making, communication.

Communication Modules:

- Each dustbin has an **ESP8266** module that sends status updates to the robot's **ESP32** when full. The robot then autonomously navigates to the bin, guided by **GPS, ultrasonic data**, and **camera vision**. Bin location and status are logged and used for routing decisions. The system can also be switched to RF in future versions using **NRF24L01.**

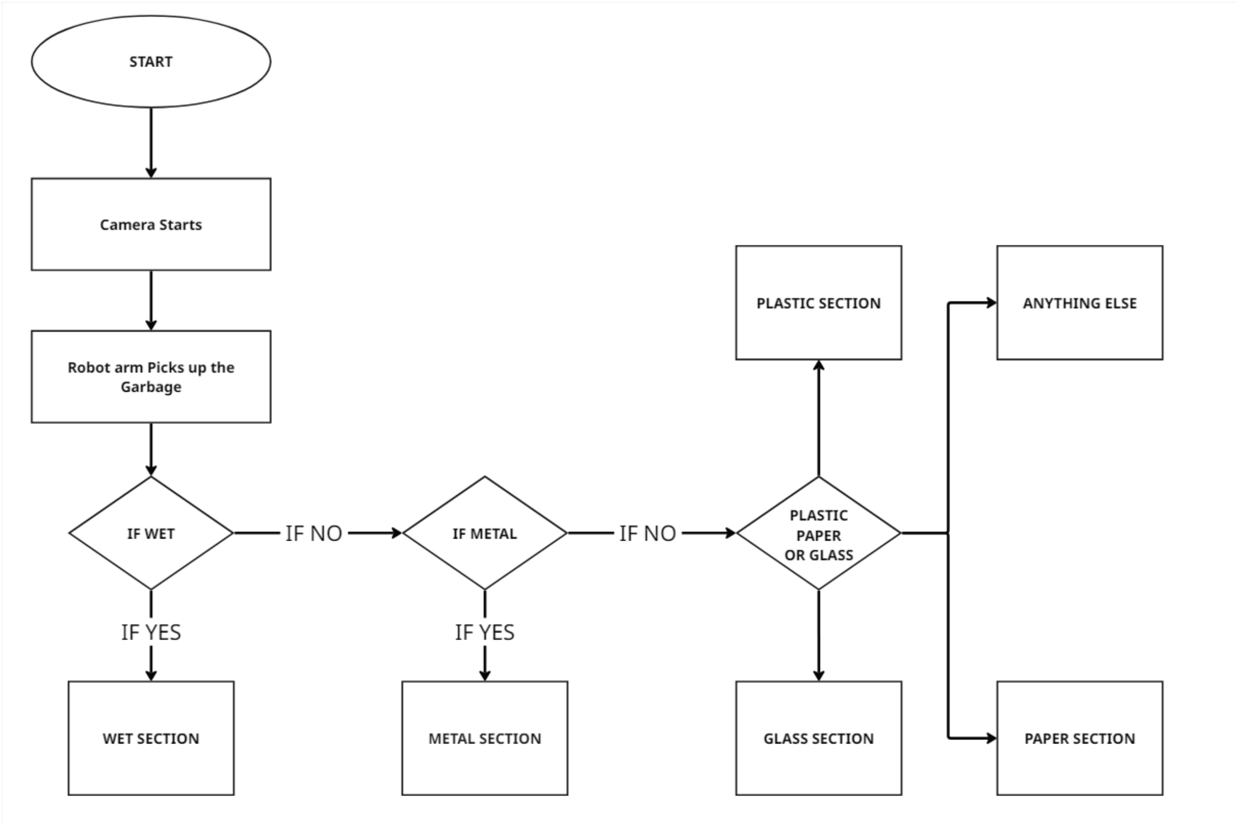
Administrative Interface:

- Real-time robot location and status
- **Smart bin status** (empty/full)
- **Maps integration** to show the positions of bins and the robot
- Control options and logs for waste management activities

Autonomous Navigation:

- **Ultrasonic Sensors (4-directional):**
  Detect obstacles and enable safe manoeuvring in city environments.
- **Camera (ESP32-CAM):**
  Provides real-time visual feedback to assist in object recognition, bin alignment, and path verification.
- **Predefined Pathways or Coordinates:**
  If the city layout is mapped, the robot can use **pre-programmed paths** or bin coordinates to optimise movement.

8. Waste Classification Pipeline:



Each piece of waste is evaluated through a **multi-step AI-driven pipeline**:

1. **Visual Detection:**
   The **ESP32-CAM** locates a piece of trash on the tray.
2. **Moisture Check:**
   The robotic arm brings the **moisture sensor** close to the object:
   - If **wet**, it goes to the **wet waste compartment**.
3. **Metal Detection:**
   The object is passed over the **open circuit metal detector**:

   - If **metal**, it is placed in the **metal compartment**.

4. **AI-Based Material Classification (Camera + LLM):**
   If neither wet nor metal:
   - The **camera** checks shape, color, and texture.
   - **LLM/AI model** classifies it as **paper**, **glass**, **plastic**, or **others**.
5. **Final Placement:**
   The object is dropped into the relevant compartment. If no criteria match, it's sent to the **'others' compartment**.

9. Coding of the Solution:

The coding of the Autonomous Urban Robotic Waste Segregator (AURo) involves programming the Arduino Mega, ESP32-CAM, and ESP8266 modules for sensor interfacing, AI-based waste classification, navigation, and wireless communication. Here's a breakdown:

Microcontroller:

Arduino Mega (Main Controller):

- **Sensor Interface:**
  Code will acquire input from:
  - **Ultrasonic sensors** (4 directions for navigation)
  - **Soil moisture sensor**
  - **Open circuit metal detector**
- **Motor & Servo Control:**
  The Arduino will control:
  - **Motor driver** for wheel movement
  - **4 servo motors** for the robotic arm's joints
- **Decision Logic:**
  Code will:
  - Perform **sensor value checks** (moisture and metal)
  - Route trash to the appropriate compartments
  - Send signals to actuate arm movements based on object classification
- **Communication:**
  It will handle **serial communication** with the **ESP32-CAM** and **ESP8266**, ensuring coordination between modules.

ESP32-CAM (Vision and LLM):

- **Camera Operations:**
  Programmed to:
  - **Capture images** of trash on the tray
  - Stream or transmit frames for analysis
- **Object Classification:**
  Using **pretrained models** or interfaced LLMs to:
  - Detect **paper, glass, plastic**, or classify them into **others**
  - Guide the robotic arm to correct pick-up and drop points
- **Feedback to Arduino:**
  The classification result is sent to Arduino via **serial commands**, initiating the sorting procedure.

ESP8266 (Smart Bin Communication):

- **Dustbin Status Detection:**
  Continuously reads the **ultrasonic sensor** to detect when the bin is full.
- **Wireless Transmission:**
  Sends a **bin-full alert** and **location ID** to the robot's ESP32 using **ESP-NOW protocol**.
- **RF** can be used in the future.

LLM/AI Integration (via API):

- **Classification Server/API:**
  - Hosted on the cloud
  - Receives the image from ESP32-CAM
  - Uses an AI model, **Gemini 2.5 flash** to classify the item
  - Returns a JSON with the predicted waste type
- **Model Logic:**
  - Trash is classified as **wet**, **metal**, **paper**, **plastic**, **glass**, or **other**

10. Cost Estimation:

Component/Module	Quantity	Unit Cost (₹)	Total Cost (₹)
Arduino Mega	1	850	850
ESP32-CAM	1	600	600
ToF Sensor (VL53L0X)	1	250	250
Ultrasonic Sensors (HC-SR04)	4	80	320
Motor Driver (L298N)	1	150	150
DC Motors with Wheels	4	300	1200
Robotic Arm (4-DOF)	1	1800	1800
Servo Motors (for arm)	4	180	720
Battery Pack (12V/9V)	1	900	900
ESP8266 for Smart Dustbins	1	250	250
Mini Vibration Motor	6	50	300
Ultrasonic Sensors for Bins	1	80	80
Metal Sensor Module	1	350	350
Soil/Moisture Sensor	1	200	200
Chassis & Frame (metal/plastic)	1	1000	1000
Misc (wires, PCB, nuts, etc.)	–	–	500

11. Business Preview

Market Opportunity

India alone generates over 62 million tonnes of waste annually. **Urban centers are under increasing pressure to manage waste more effectively and sustainably.** Municipalities are actively seeking **smart city technologies to improve cleanliness, efficiency, and resource management.**

AURo directly addresses:

- **Labour shortages in waste collection.**
- **Delayed pickups due to manual scheduling.**
- **Improper segregation leads to pollution and landfill overflow.**

Target Customers

- **Municipal Corporations (Tier 1 & Tier 2 cities).**
- **Private Waste Management Contractors.**
- **Smart City Projects under the Government of India initiatives.**
- **Large housing societies, townships, and campuses.**

Business Model

1. **B2G (Business to Government):** Offer AURo as a deployable system to urban local bodies.

2. **B2B (Business to Business):** Collaborate with facility management companies, hospitals, and IT parks for localised deployment.

Scalability

The modular nature of the system allows for:

- Adding multiple smart bins to any city layout.
- Deploying more AURo units for different zones.
- Integrating cloud-based analytics for performance and waste generation trends.

Revenue Streams

- **Sale of AURo Units: One-time cost + optional annual maintenance.**
- **Subscription for Smart Bin Software & Monitoring.**

- **Custom Integrations for specific industrial or environmental use cases.**

Competitive Advantage

- **Combines AI-driven waste classification, autonomous mobility, and IoT-enabled bins—unlike most current semi-manual solutions.**
- **Lower cost of deployment compared to existing industrial robotic solutions.**
- **High adaptability to Indian urban infrastructure.**

12. Challenges Faced During the Development Process

1. Integration of Hardware and Software

- Ensuring **seamless coordination** between **sensors, motors, and actuators** with software logic on the **Arduino Mega and ESP32-CAM** was complex.
- Frequent **hardware-software interface bugs** required rigorous debugging and testing.
- Synchronising **arm control with classification results** demanded precise timing and multi-device communication.

2. Real-Time Data Transmission

- Establishing **reliable wireless communication** between the **smart bins (ESP8266) and the robot (ESP32)** in urban conditions was difficult.
- **Packet loss, latency, and Wi-Fi interference** in populated areas affected performance.
- Ensuring **real-time coordination** with limited bandwidth was a key hurdle.

3. Algorithm Optimisation

- Running **image classification and sorting logic on limited microcontroller resources** posed computational constraints.
- Balancing **processing speed, accuracy, and power consumption** required **fine-tuning algorithms.**
- Efficiently handling **parallel tasks like movement, sorting, and communication** was essential but **challenging.**

5. Environmental and Real-World Factors

- **Variability in lighting conditions, outdoor temperature, and trash surface wetness impacted sensor accuracy and camera reliability.**
- **Dust, water, and vibrations** affected the **mechanical performance of components.**
- Designing a **robust enclosure and durable mechanisms** was essential to ensure long-term operation in public spaces.

13. Social Impact & Innovation

Cleaner Cities, Healthier Communities

- AURo directly addresses the issue of **uncollected and mismanaged waste**, which leads to **pollution, disease outbreaks**, and **clogged urban infrastructure**.
- By **automating waste segregation and collection**, AURo helps keep **streets clean**, reducing the risks of diseases like **dengue, malaria**, and **cholera** caused by waste accumulation and stagnant water.

Revolutionising Waste Management

- With **onboard classification systems** and **segregated compartments**, AURo sorts trash into **wet, metal, plastic, glass, paper**, and **others,** drastically improving **recycling efficiency**.
- Reduces dependency on manual labour in waste sorting, **minimising human exposure** to hazardous waste.-

Empowering Municipal Services

- Robots can work **24/7**, enabling more frequent and precise waste collection, even in **remote or congested areas**.

LLM-Driven Approach

- Integration with **Large Language Models (LLMs)** enables **intelligent decision-making**, communication with servers, and adaptability to **dynamic environments**.

Collaboration and Importance

Municipal Corporations and Urban Planners

- Essential for deploying AURo across city zones, setting up **smart dustbins**, and **mapping waste hotspots**.
- Collaboration ensures **policy alignment**, infrastructure compatibility, and **long-term adoption**.

Citizens and Local Communities

- Encouraging citizens to **use smart bins correctly** and **engage with clean city initiatives** increases system effectiveness.
- Promotes **eco-conscious behaviour**, **community responsibility**, and public support.

Concrete Example of Application

Scenario: A mid-sized city like **Jaipur** integrates AURo with its smart waste management infrastructure.

- **Who Would Use It**:
  Municipal cleaning departments, **urban planning authorities**, and **AI-driven fleet management systems**.

- **Beneficiaries**:
  City residents, particularly in **high-density urban zones,** where waste mismanagement is a daily problem.

- **Impact**:
  AURo ensures **timely pickup**, **on-the-spot segregation**, and **eco-friendly processing** – leading to **cleaner streets**, **healthier air**, and **increased recycling rates**, while also **saving public funds**.

List of Sources:

Websites:

- https://www.researchgate.net/publication/350437509_Intelligent_Waste_Management_System_Using_Artificial_Intelligence
- https://ieeexplore.ieee.org/document/9355585
- https://en.wikipedia.org/wiki/Waste_separation
- https://swachhbharatmission.gov.in/

People: Manpreet Kaur(Robotics teacher at CCWS) & Nisha Sharma(HOD of Science at CCWS)