

# SOLAR-POWERED TERRAIN-ADAPTIVE CONTROL & AI- DRIVEN LOCOMOTION FOR AUTONOMOUS ECO ROVER NAVIGATION

Ashuthosh VP<sup>1</sup>, Adarsh KB<sup>2</sup>, Rishwan K<sup>3</sup>, Fathima Sapna P<sup>4</sup>, Jasmine P<sup>5</sup>

<sup>1,2,3</sup>Graduate Student, <sup>4,5</sup>Associate Professor Department of Electrical and Electronics  
AWH Engineering College Calicut, Kerala, India

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**Abstract** - This paper presents the design, modeling, and implementation of a solar-powered terrain-adaptive autonomous Eco-Rover intended for sustainable coastal and outdoor environmental applications. The proposed system integrates a photovoltaic energy harvesting module, lithium-ion battery storage with Battery Management System (BMS), Maximum Power Point Tracking (MPPT), closed-loop PWM-based motor control, and AI-assisted navigation using multi-sensor fusion. A tracked skid-steer locomotion mechanism ensures improved traction and reduced ground pressure over deformable sandy terrain. Real-time feedback from encoders and IMU enables adaptive slip correction and stability enhancement. Obstacle detection is achieved using ultrasonic sensing and camera-based perception, while GPS-based geofencing ensures boundary-constrained operation. Experimental validation demonstrates improved energy efficiency, terrain adaptability, and autonomous reliability, establishing the Eco-Rover as a scalable platform for renewable-powered robotic mobility systems.

**Key Words:** Autonomous Rover, Solar Energy System, MPPT, Terrain-Adaptive Control, Skid Steering, GPS Geofencing, Embedded Systems.

## 1. INTRODUCTION

Environmental degradation in coastal regions has intensified due to plastic waste accumulation and human activities. Traditional manual cleaning approaches are labor-intensive, inconsistent, and inefficient for large-scale coverage. Autonomous robotic systems offer a scalable and energy-efficient alternative capable of extended deployment with minimal human supervision. However, designing an outdoor rover for sandy terrain presents several engineering challenges.

Sand introduces high rolling resistance, reduced traction, and unpredictable slippage. Moreover, coastal deployment environments often lack reliable grid power, necessitating renewable energy integration. Therefore, an efficient robotic platform must simultaneously address mobility, energy sustainability, and intelligent navigation.

The proposed Eco-Rover integrates renewable solar energy harvesting, hybrid battery storage, adaptive locomotion control, and sensor-fusion-based navigation into a unified embedded system. The objective is to develop a reliable, energy-independent, and terrain-adaptive robotic platform capable of autonomous outdoor operation under varying environmental conditions.

## 2. LITERATURE REVIEW

Recent literature emphasizes the need for autonomous coastal cleanup to mitigate marine plastic accumulation [10] and reduce the occupational hazards associated with manual waste collection [9]. Early robotic solutions, such as the Prometeo platform [2] and FEM-analyzed trailers [4], effectively targeted debris removal but struggled with the high rolling resistance of sandy terrain. To overcome this, tracked platforms like the 'Hirottaro' robot [5] were introduced, significantly improving traction and maneuverability on uneven sand. The design and validation of such mobile robotic structures have been further accelerated by ROS and Gazebo simulation environments [8].

Concurrently, advancements in SLAM algorithms [7], GPS-guided platforms like the 'Binman' robot [1], and radio-controlled cleaning bots [3] have significantly improved outdoor autonomous routing. Additionally, studies by Begum et al. [6] have demonstrated the efficacy of IoT-driven predictive analytics for optimizing off-grid solar power. However, current research largely addresses terrain mobility, intelligent navigation, and renewable energy integration as isolated challenges. The proposed Eco-Rover bridges this critical gap by integrating MPPT-optimized solar harvesting, tracked skid-steer locomotion, and AI-assisted geofencing into a unified autonomous platform, uniquely equipped with a specialized cleaning module featuring round brushes and a board-mounted water sprinkler to maximize environmental adaptability. Ultimately, this research provides a scalable, energy-independent framework designed to significantly enhance continuous operational endurance in challenging coastal environments.

### 3. SYSTEM ARCHITECTURE

#### 3.1 Overall Architecture

The Eco-Rover is centered around a ESP32 controller interfacing with sensing, power, and actuation modules. The hardware architecture includes:

- Photovoltaic panel
- MPPT charge controller
- Lithium-ion battery pack Battery Management System (BMS)
- Dual DC motors with tracked drive
- Motor driver module
- Ultrasonic sensors
- Camera module
- IMU sensor
- GPS receiver

The modular structure ensures scalability and simplified maintenance.

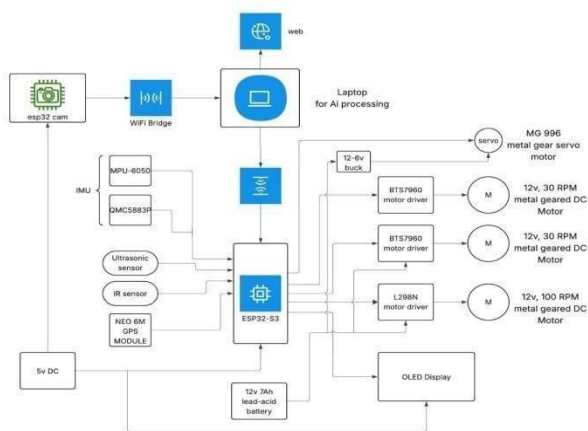


Figure 1:- Block Diagram

#### 3.2 Power Management System

The photovoltaic module generates electrical energy governed by:

$$P=V \times I$$

where P is power output, V is panel voltage, and I is current.

To maximize energy extraction, an MPPT controller continuously adjusts operating voltage to maintain operation at the maximum power point under varying irradiance conditions.

The energy balance equation of the system is expressed as:-

$$P_{solar} + P_{battery} = P_{motors} + P_{control} + P_{sensors}$$

This ensures that energy demand does not exceed available supply. Excess solar energy charges the battery, while stored energy supports operation during low sunlight conditions.

The BMS ensures:

- Over-voltage protection
- Under-voltage protection
- Over-current protection
- Thermal monitoring
- Balanced charging

Regulated outputs provide 5V for logic circuits and 12V for locomotion motors.

#### 3.3 Locomotion System

The rover employs a tracked skid-steer configuration to reduce ground pressure and improve traction. Ground pressure is defined as:

$$P = W/A$$

where W is total weight and A is contact area. Increasing contact area reduces sinking in soft sand.

Turning is achieved through differential drive control. Angular velocity depends on speed difference between left and right tracks.

Motor voltage is controlled using PWM modulation:  $V_{avg} = D \times V_{supply}$  where D represents duty cycle.



Figure 2:- Tracked Drive Mechanism

## 4. CONTROL STRATEGY

### 4.1 Energy Management Layer

The energy management layer monitors battery voltage and solar input to ensure stable operation. The MPPT controller maximizes photovoltaic power extraction under varying irradiance conditions. Battery levels are maintained within safe limits to prevent over-discharge. When energy drops below a threshold, motor speed is reduced to extend runtime.

### 4.2 Locomotion Control Layer

Encoder feedback enables closed-loop speed control. Slip ratio is calculated by comparing commanded speed with measured RPM. If slip exceeds threshold:

- PWM duty cycle is reduced
- Torque distribution is adjusted

This improves traction stability on uneven sand.

### 4.3 Navigation and Obstacle Avoidance

Obstacle detection combines ultrasonic sensing and camera-based perception. Sensor fusion reduces false detection under uneven lighting conditions.

When obstacle distance  $d < d_{\text{threshold}}$  :-

- Rover halts
- Directional scan is performed
- Alternate path is computed

After clearance, the rover resumes original trajectory.

### 4.4 Vision System and AI Processing

To enable intelligent obstacle avoidance and waste identification, the Eco-Rover employs a vision-based Artificial Intelligence module powered by the YOLOv8 (You Only Look Once) object detection algorithm. YOLOv8 was selected for its state-of-the-art processing speed and high mean Average Precision (mAP), making it highly suitable for real-time visual analysis in dynamic coastal environments.

The AI model was trained on a custom, domain-specific dataset tailored for beach environments. This dataset was systematically managed, augmented, and merged utilizing the Roboflow platform to ensure robust detection of various terrain obstacles and specific litter types. Model training was executed utilizing Google Colab to leverage cloud-based GPU acceleration.

The resulting optimized model processes the live video feed streamed from the rover's camera. During operation, the deep-learning algorithm continuously analyzes incoming visual frames, classifies detected objects (e.g., debris, natural obstacles), and relays directional feedback to the central control unit. This seamless integration between the YOLOv8 perception layer and the locomotion control layer allows the rover to dynamically execute path re-routing and intelligent navigation with minimal latency.

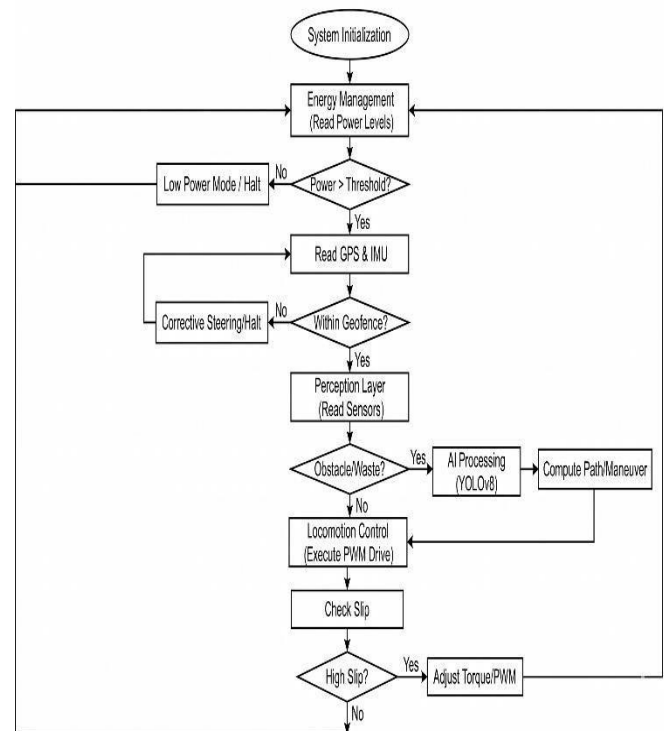


Figure 3:- Flow Chart

## 5. GPS-BASED GEOFENCING

Operational boundaries are defined using predefined latitude and longitude coordinates. Real-time GPS data is continuously compared with stored limits.

If deviation exceeds tolerance:

- Corrective steering is applied
- Emergency halt is triggered if necessary

This prevents unintended exit from designated operational zones. Furthermore, upon stabilization, the navigation algorithm computes the optimal return trajectory to safely guide the rover back into the active working area.



Figure 4:- GPS Perimeter Control

## 6. PERFORMANCE ANALYSIS

Experimental validation was conducted under simulated sandy terrain conditions.

Observations include:

- Tracked configuration reduced sinking compared to wheeled systems
  - Closed-loop control maintained consistent RPM under load variation
  - Solar charging increased operational endurance by 35–40% during peak irradiance
  - Sensor fusion reduced obstacle detection errors
- Energy efficiency improved due to MPPT optimization and intelligent load management



Figure 5:- Prototype Model of Eco-Rover

## 7. FUTURE ENHANCEMENTS

Future improvements may include:

- LIDAR integration
- Reinforcement learning path planning
- Cloud telemetry for remote monitoring
- Lightweight composite chassis materials

## 8. CONCLUSION

The proposed Eco-Rover integrates renewable energy harvesting, adaptive locomotion, intelligent navigation, and geofencing into a unified embedded system. The hybrid solar-battery architecture ensures sustainable long duration operation, while closed-loop slip correction enhances terrain stability. The developed system establishes a scalable foundation for renewable-powered autonomous robotic platforms suitable for environmental and outdoor applications.

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