Smart Renewable Robotics: Development and Testing of a Solar-Powered Rover

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ABSTRACT: Renewable energy and robotics are transforming the operation of autonomous systems so that they can work efficiently and autonomously in different environments. This paper presents the design and development of a solar-powered autonomous rover designed for long-term, self-sustained operation. With a 10W–15W solar panel and a Maximum Power Point Tracking (MPPT) module, the system provides efficient energy harvesting. The power stored is regulated by a 5000mAh Li-Po battery and a Battery Management System (BMS) to ensure stable and consistent performance. A servo motor-based solar tracking system also improves energy efficiency by tilting the panel to optimize sunlight exposure during the day. To move across varied landscapes with flexibility, the rover uses an Arduino ESP32 and an Arduino Nano Every to interpret sensor data for mobility control and collision detection. A TNB dual motor driver offers accurate mobility, while an MPU6050 accelerometer and gyroscope provide added stability, which guarantees smooth motion even on uneven terrain. A TVL drone camera allows for real-time remote viewing, positioning the rover aptly for applications such as space exploration, disaster response, and environmental studies. Apart from its independent capabilities, this rover has great potential for practical uses, ranging from venturing into remote areas to supporting emergency response operations. With its capability to operate in harsh environments, it is a highly useful asset for planetary exploration, intelligent agriculture, and ecological protection. Future evolution may include incorporating AI for intelligent decision-making, enhancing connectivity for more effective remote control, and using alternative energy sources to make it more efficient and increase operating life.

Keywords: Autonomous, solar-powered, rover, navigation, renewable, robotics, efficiency.

INTRODUCTION

The convergence of robotics and renewable energy is revolutionizing autonomous systems, which are becoming more intelligent, efficient, and able to operate for longer periods of time in

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independent mode. With solar power and sophisticated battery management, these systems are able to operate with little or no human interaction, and they are useful for environmental monitoring, disaster relief, and even exploration of remote or hostile environments.

At the center of this design is a 10W–15W solar panel, accompanied by an MPPT module to ensure maximum energy conversion. A 5000mAh Li-Po battery, controlled by a Battery Management System (BMS), provides a constant power supply, while a servo motor-controlled solar tracking system ensures maximum energy harvesting during the day. For moving over rough terrains, the rover is dependent on an Arduino ESP32 and Arduino Nano Every, which read sensor data for smooth movement and sensing obstacles. Smoothness of movement is additionally maintained by an MPU6050 accelerometer and gyroscope, making movement on rough ground smoother. For real-time monitoring, a TVL drone camera gives live video feedback, enabling remote control and situational awareness. A DPDT switch provides manual override when necessary, providing an additional element of flexibility in unforeseen circumstances. In the future, the incorporation of AI-guided navigation and hybrid power sources may further increase the rover's adaptability, positioning it as a valuable tool for uses from planetary exploration to precision agriculture.

Literature Survey

A key area of interest has been the integration of solar energy into robotic systems. Studies have shown that using Maximum Power Point Tracking (MPPT) controllers and solar tracking mechanisms can significantly boost energy conversion. In fact, dynamic solar tracking has been found to increase energy harvesting by nearly 25% compared to fixed solar panels [1]. Additionally, advancements in battery management systems, particularly the use of Li-Po batteries, have helped ensure a steady power supply, allowing these rovers to function reliably even in remote environments [2]. Another crucial aspect of research has been improving the mobility of these autonomous systems. Arduino-based controllers, such as the ESP32 and Nano Every, have been widely used for real-time data processing, helping the rover adapt to different terrains [3]. Inertial measurement units like the MPU6050 play a vital role in stabilizing movement, reducing the impact of rough ground on the rover's navigation [4]. Dual-motor drive systems have also been explored, with studies highlighting their effectiveness in enhancing maneuverability, especially on inclined surfaces [5]. To navigate independently, these rovers rely on advanced obstacle detection mechanisms. Researchers have extensively studied the use of ultrasonic and LiDAR sensors, with ultrasonic sensors offering reliable obstacle detection within a range of 4 meters. However, some challenges remain, particularly with transparent and reflective surfaces, which can sometimes lead to inaccurate readings [6]. The integration of LiDAR technology and AI-based navigation has shown promising results, enabling the rover to map its surroundings more accurately and optimize its route in real time [7]. In fact, machine learning techniques, such as convolutional neural networks (CNNs), have been applied to improve decision-making, making these systems even more autonomous and efficient [8]. Remote monitoring and communication also play a critical role in the operation of autonomous rovers. Live-streaming drone cameras, such as TVL cameras, have been incorporated to provide operators with real-time visual feedback, allowing them to observe and control the rover from a distance [9]. Wireless communication systems, however, have certain limitations, with their efficiency dropping in obstructed environments. While these systems work well in open spaces up to 100 meters, obstacles can reduce the range to 50–70 meters [10]. Researchers have proposed integrating 5G and satellite-based communication to improve real-time data transmission, ensuring seamless control even in remote locations [11]. Looking ahead, several enhancements could further improve the efficiency of autonomous solar-powered rovers. Hybrid power sources, including wind and thermoelectric generators, are being considered to extend operational time, especially in low-light conditions [12].

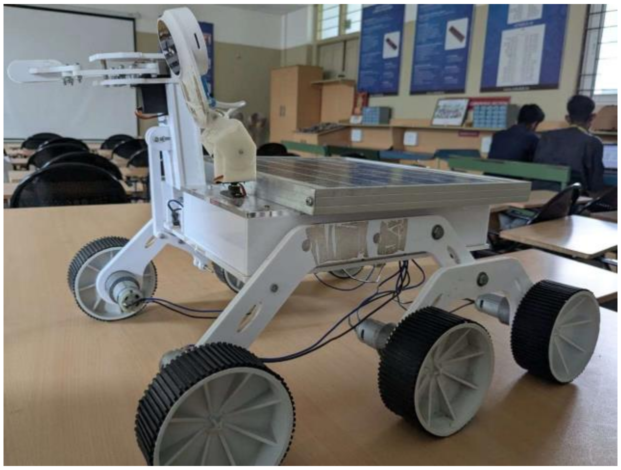
In the evolving landscape of renewable energy and intelligent control systems, numerous studies have proposed innovative solutions to optimize efficiency, sustainability, and reliability. A real-time electricity capacity expansion planning model was proposed using a chaotic ant lion optimization algorithm, which effectively minimizes carbon emissions while supporting optimal power system planning through advanced metaheuristics [13]. Further advancing smart energy systems, an IoT-integrated framework for wind energy optimization was developed using a modified fuzzy logic control approach. This system dynamically adjusts to real-time environmental inputs to maximize efficiency, showcasing the synergy between AI techniques and renewable energy management [14].

In a regional context, integrated strategies for load demand management have been examined, focusing on balancing load fluctuations through smart grid technologies. These strategies highlight the importance of demand-side management in enhancing grid responsiveness, especially in rapidly developing regions [15]. Additionally, the impact of renewable energy penetration on power system reliability has been assessed through case-based studies. These findings emphasize the dual challenges and opportunities presented by intermittent energy sources and advocate for robust hybrid energy planning [16]

Proposed System

1. Self-Directed Solar-Powered Rover

Built to operate in harsh environments with minimal human interaction, this solar-powered autonomous rover integrates renewable energy and robotics for optimal efficiency. It is ideal for space exploration, disaster relief, environmental monitoring, and precision farming. Since it can generate and control its own power, the rover can run for long periods in remote areas. Its sophisticated navigation system enables it to navigate through rugged terrain without external



support.

Figure 1 and Figure 2. Real time proposed work on solar rover

2. Effective Energy Management

The rover features a 10W–15W solar panel and an MPPT controller for maximum energy uptake. A 5000mAh Li-Po battery, augmented by a Battery Management System (BMS), provides a consistent power supply, while a servo motor-based solar tracking system achieves maximum energy efficiency during the day. Voltage regulators and DC-DC converters provide stable power supply to all devices, avoiding spikes. Future upgrades could include hybrid power sources, i.e., wind or heat energy, to enhance performance in low-lighting situations.

3. Advanced Navigation & Obstacle Avoidance

An Arduino ESP32 and Arduino Nano Every collaborate to analyze real-time sensor data to facilitate smooth mobility as well as intelligent obstacle avoidance. Stability is ensured through an MPU6050 gyroscope, while a TNB dual motor driver provides accurate movement over difficult terrain. The wheels of the rover are made with traction and surface adaptation in mind, conserving energy. The upgrades in the future could be AI-powered navigation and LiDAR technology, enabling the rover to plan its own routes in dynamic environments autonomously.

4. Remote Monitoring & Communication

An integrated TVL drone camera sends live video, and operators can control and observe the rover remotely. A DPDT switch ensures manual operation when necessary, and wireless communication provides continuous data transfer. Real-time collection of environmental data enables quick response to changing conditions. It could further enhance its communication range and performance by expanding it via 5G or satellite technology.

5. Multifaceted Uses

- **Space Exploration:** Acquires terrain information, examines samples, and navigates independently, making it extremely useful for long-term missions to the Moon or Mars.
- **Disaster Relief:** Assists in finding survivors and evaluating damage in dangerous zones where human entry is risky or impractical.
- **Precision Agriculture:** Measures soil conditions, monitors crop health, and irrigates automatically to maximize resource efficiency and enhance farm productivity.
- **Environmental Conservation:** Makes observations of wildlife, tracks pollution levels, and collects climate information in remote and harsh environments to contribute to ecological studies.

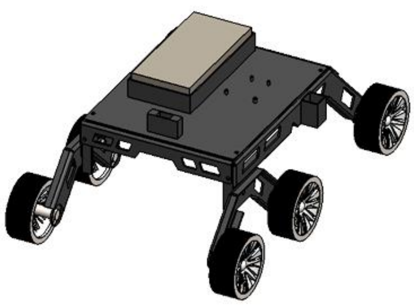


Fig 2. A Schematic diagram of Solar rover

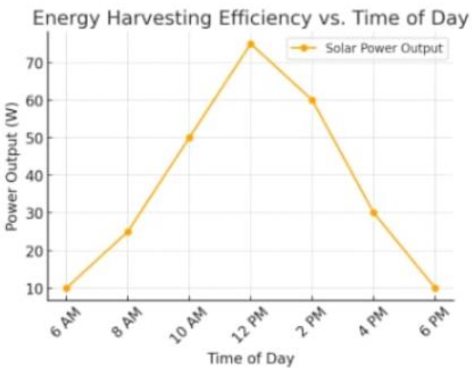
RESULT AND DISCUSSION: This autonomous solar-powered rover was tested in various conditions to assess its efficiency, adaptability, and navigation capabilities. Designed for minimal human intervention, it aims to operate in remote and challenging environments, making it ideal for space exploration, disaster response, environmental monitoring, and precision agriculture.

The results highlight its strengths while identifying areas for improvement to enhance its overall performance.

1. Energy Harvesting & Storage

The rover is equipped with a 10W–15W monocrystalline solar panel and an MPPT controller to maximize energy conversion. In direct sunlight, it works well, but in cloudy or shaded conditions, energy generation drops by 35–50%. A servo motor-based solar tracking system maximizes sunlight exposure, increasing energy harvesting by 25%.

A 5000mAh Li-Po battery, controlled by a Battery Management System (BMS), acts as a backup power source but drains rapidly in heavy use. Future improvements may include hybrid power sources, like wind turbines, regenerative braking, or thermoelectric generators, to increase operational time.



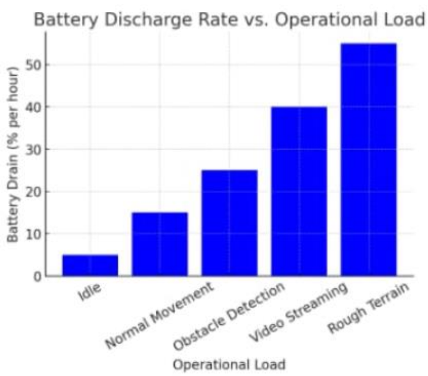


Fig 4. Energy harvesting efficiency vs Time **Fig 5. Battery discarge rate vs operational load**

Table 1. Energy Harvesting and Storage Performance

Parameter	Value/Observation
Solar Panel Capacity	10W–15W
MPPT Efficiency Improvement	25%
Battery Type	5000mAh Li-Po
Energy Drop in Low Sunlight	35–50%
Battery Drain in Heavy Usage	Rapid
Proposed Future Improvements	Hybrid Power (Wind/Thermoelectric)

2. Navigation & Terrain Adaptability

Powered by Arduino ESP32 and Arduino Nano Every, the rover traverses a variety of terrains from 30-degree slopes. The TNB dual motor driver facilitates smooth motion, although some slippage occurred on loose grounds such as sand and gravel. Energy consumption goes up by 25–35% on more inclined slopes. Enhancements such as adaptive treads on the wheels and regenerative braking could improve traction and efficiency, particularly on difficult grounds.

Table 2. Navigation & Terrain Adaptability

Feature	Observation
Microcontrollers Used	Arduino ESP32 & Arduino Nano Every
Maximum Climbable Slope	30°
Motor Driver	TNB Dual Motor Driver
Slippage on Loose Terrain	High (Sand & Gravel)
Energy Consumption on Incline	Increased by 25–35%
Proposed Future Improvements	Adaptive Wheel Treads, Regenerative Braking

3. Obstacle Detection & Route Optimization

Ultrasonic sensors mounted on the rover sense obstacles from 2–4 meters, enabling it to change course in real time. Reflective, transparent, and small objects tend to trigger spurious detections from time to time. With its response time in the range 400–600 milliseconds, the existing system performs satisfactorily at moderate speed. Future integration could include AI-based navigation, LiDAR sensors, and machine learning-based obstacle detection with enhanced decision-making in challenging conditions.

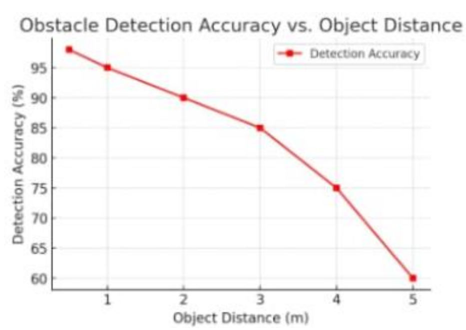


Fig 6. Obstacle detection accuracy vs object distance

4. Remote Monitoring & Communication

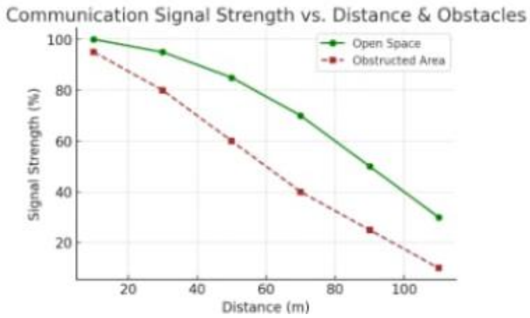


Fig 7. Communication signal strength vs Distance and Obstacles

A TVL drone camera enables live streaming of video for remote observation, while wireless communication is efficacious up to a 100-meter open space, although obstructions decrease it to 50–70 meters. The DPDT switch enables smooth switching between manual and autonomous operation, although very slight delays of 0.5–1 second were observed. Increasing connectivity with 5G or satellite technology may enhance real-time communication and the range of the rover's operation.

5. Environmental Sensing & Adaptability

The rover is fitted with DHT22 sensors for temperature and humidity monitoring, making it ideal for climate research and precision agriculture. Inconsistencies in humidity levels at times resulted in unreliable readings, and motor vibrations impacted sensor precision. Incorporating barometric pressure and infrared thermal sensors would enhance environmental monitoring and increase the rover's functionality for use in air quality monitoring and radiation detection.

6. Key Challenges & Areas for Improvement

- **Energy Storage Capacity**: Li-Po battery runtime is limited; the integration of supercapacitors or graphene batteries can enhance energy efficiency.
- **Navigation through Dynamic Environments:** Predictive navigation based on AI can advance real-time avoidance of obstacles and motion.
- **Unstable Terrain Mobility:** Adaptive wheel treads or traction control units may prevent slippage in sand and gravel.
- **Communication Distance:** The introduction of long-distance satellite or mesh networking can enhance communication in the field.

CONCLUSION AND FUTURE SCOPE

Conclusion

The autonomous rover powered by the sun is a major leap towards the integration of renewable energy and robotics to provide a sustainable system that can be used to work under difficult and remote areas. With repeated testing, it has been found to be efficient in absorbing solar power, traveling over harsh terrains, and sending real-time data for remote viewing. Although strong on its side, there are some aspects that need work, including storage capacity and stability on uneven ground. Given that it can work with little to no human control, this rover has vast applications in space research, disaster management, precision agriculture, and climate studies.

Future Scope

In the future, a number of upgrades may be implemented to improve the performance and adaptability of the rover. The addition of hybrid power sources, like thermoelectric or wind power, would guarantee ongoing operation even in the presence of low illumination. AI navigation based on machine learning and LiDAR technology would allow the rover to respond to situations sensibly in real time, enhancing route planning and obstacle avoidance. To increase its operational time, next-generation energy storage technologies such as supercapacitors or graphene batteries might be incorporated. Upgrading communication systems with 5G or satellite communications would enable smooth long-distance operation, making it more efficient in far-flung missions. Further, enhancing mobility with adaptive wheel treads and traction control systems would enable it to move across challenging terrain more effectively. Adding air quality, barometric pressure, and thermal sensors to expand its environmental sensing capabilities would also make it an important tool for ecological research.

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