System-Level Design and Outdoor Validation of a Solar-Powered Mobile Robot for Autonomous Environmental Monitoring

Diseño a Nivel de Sistema y Validación en Exteriores de un Robot Móvil Solar para la Monitorización Ambiental Autónoma

Projeto ao Nível do Sistema e Validação Externa de um Robô Móvel Alimentado a Energia Solar para Monitorização Ambiental Autónoma

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Summary. - The need to explore and use mobile robots outside is rising, mainly in terms of monitoring the environment and conducting inspections outside grid resources, where energy autonomy, terrain variability, and communication are essential. The purpose of this paper is to propose an innovative solar-powered mobile robot that integrates solar energy harvesting, four-wheel drive, two channels of wireless communication, and passive thermal management. The majority of previous works emphasized and focused on single components and experimental investigations, while this paper instead focuses on experience with practical implementations of these technologies outside, thereby gaining experience with similar robots outside, leading to observations on energy efficiency, movement, control, and communication, with possible implications for improving the next generation of robots outside. The experiment outside using various terrain types of grass, gravel, and earth successfully proved the positive energy balance of the robot, easy energy-efficient motion, good wireless control, and good wireless video streaming with little delay.

Keywords: *Solar-powered robots, Terrain-adaptive locomotion, Energy harvesting, Autonomous mobile robots, Off-grid monitoring.*

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Resumen. - *La necesidad de explorar y utilizar robots móviles en exteriores es cada vez mayor, principalmente para la monitorización del entorno y la realización de inspecciones fuera de la red eléctrica, donde la autonomía energética, la variabilidad del terreno y la comunicación son esenciales. El objetivo de este trabajo es proponer un innovador robot móvil solar que integra la captación de energía solar, tracción en las cuatro ruedas, dos canales de comunicación inalámbrica y gestión térmica pasiva. La mayoría de los trabajos previos se centraban en componentes individuales e investigaciones experimentales, mientras que este trabajo se centra en la experiencia con implementaciones prácticas de estas tecnologías en exteriores, obteniendo así experiencia con robots similares en exteriores, lo que ha llevado a observaciones sobre eficiencia energética, movimiento, control y comunicación, con posibles implicaciones para la mejora de la próxima generación de robots en exteriores. El experimento en exteriores, utilizando diversos tipos de terreno como césped, grava y tierra, demostró con éxito el balance energético positivo del robot, su fácil movimiento con eficiencia energética, su buen control inalámbrico y su buena transmisión de vídeo inalámbrica con poca latencia.*

Palabras clave: *Robots alimentados con energía solar, Locomoción adaptativa al terreno, Recolección de energía, Robots móviles autónomos, Monitoreo fuera de la red.*

Resumo. - *A necessidade de explorar e utilizar robôs móveis em ambientes exteriores é crescente, principalmente para monitorizar o ambiente e realizar inspeções em locais sem acesso à rede elétrica, onde a autonomia energética, a variabilidade do terreno e a comunicação são essenciais. O objetivo deste artigo é propor um robô móvel inovador alimentado a energia solar que integra a captação de energia solar, tração às quatro rodas, dois canais de comunicação sem fios e gestão térmica passiva. A maioria dos trabalhos anteriores enfatizou e focou-se em componentes individuais e investigações experimentais, enquanto este artigo se centra na experiência com implementações práticas destas tecnologias em ambientes exteriores, adquirindo experiência com robôs semelhantes em ambientes exteriores, o que leva a observações sobre eficiência energética, movimento, controlo e comunicação, com possíveis implicações para a melhoria da próxima geração de robôs para uso exterior. A experiência externa, utilizando vários tipos de terreno (relva, cascalho e terra), comprovou com sucesso o balanço energético positivo do robô, a facilidade de movimento com eficiência energética, o bom controlo sem fios e a boa transmissão de vídeo sem fios com baixa latência.*

Palavras-chave: *Robôs movidos a energia solar, Locomoção adaptativa ao terreno, Captação de energia, Robôs móveis autónomos, Monitorização fora da rede elétrica.*

1. Introduction. - Outdoor mobile robots are being used in environmental monitoring, precision agriculture, surveillance, and inspecting infrastructural facilities, among others [1]. Such robots should be able to function well in unstructured, or off-grid environments characterized by energy autonomy, terrain flexibility, and effective communication. Typically, battery-powered robots have short missions and require quite regular servicing, particularly when they are required to operate in remote areas [2].

Solar energy harvesting has an excellent potential as a method for extending operational endurance while minimizing human intervention. However, the integration of photovoltaic (PV) systems in mobile platforms involves issues related to variable energy supply, charging efficiency, and real-time energy management [3]. Wheeled robots remain mechanically simple and energy-efficient but often suffer from performance degradation on soft or uneven terrain owing to slippage and increased power demands [4-5].

Previous research in the field of solar-powered robots has involved investigations into PV modules, energy storage, power electronics, suspension, and communication technologies. However, most studies are confined either to single subsystems or controlled laboratory conditions, or indeed specialized applications, thus providing very limited insight into system-level integration in real-life conditions. Energy harvesting, terrain-adaptive locomotion, wireless communication, and thermal performance experimental validation of a completely functional robot has barely been investigated.

This paper will address these gaps through the system-level design and outdoor evaluation of a solar-powered, terrain-adaptive mobile robot for off-grid monitoring. The approach emphasizes practical integration over component-level innovation through a holistic platform that combines photovoltaic energy harvesting, battery storage, four-wheel-drive locomotion, dual-channel wireless communication, and passive thermal management. Experimental validation across multiple terrains is presented; interaction between energy generation, terrain-dependent mobility, communication performance, and thermal stability is quantified.

The contributions of this work are highlighted as follows:

- A modular system-level architecture integrating energy harvesting, locomotion, communication, and thermal management.
- Outdoor experiments on grass, gravel, and dirt with evaluation of energy harvesting and consumption, mobility, communication latency, and thermal behaviour.
- Practical insights on trade-offs between energy autonomy, terrain adaptability, and communication reliability for off-grid monitoring robots.

2. Literature Review. - Outdoor-deployed mobile robots face challenges in terms of energy autonomy, terrain adaptability, and wireless communication. The lack of grid power supply in an outdoor environment has encouraged researchers to explore alternative sources of energy, such as renewable energy sources, especially PV systems, for efficient energy autonomy with low human intervention. Even though various reviews have been conducted on the integration of PV systems and energy efficiency, they have been more theoretical and have limited practical applications.

Practical applications of solar-powered robotics include agricultural field robots, transport robots, and experimental robots. Solar-powered surveillance robots have been found to have the potential to charge the battery while moving on any terrain in real field conditions [6]. General-purpose robots used in agricultural applications use solar power to perform several operations, including irrigation, sowing, and crop monitoring [7]. Even simple robots have been used to validate the practical applications of solar-powered robots [8-10]. Moreover, solar-powered robots have also been used for marine and industrial monitoring, which can ensure very long duration and autonomous operations [11].

Despite all these advancements, energy harvesting along with terrain-dependent mobility, wireless communication, and thermal behavior, in a unified and integrated manner, has rarely been addressed in existing platforms. In most research, carried out either in a laboratory environment or in applications where the scope of generalization is limited, subsystems have been addressed in an isolated manner. Quantitative analysis of energy balance considering load variation due to terrain has rarely been addressed. The aim of this paper is to bridge this gap by proposing a unified system design, keeping in view deployability, energy awareness, and experimentation.

Ref	Platform / Robot	Application	Solar System	Mobility / Locomotion	Key Focus / Findings	Limitations
[6]	Surveillance Robot	Agricultural field monitoring	PV panels + battery	4WD, all-terrain	Demonstrated feasibility of solar-charging for multi-day outdoor operation	Limited terrain types, short-term field test
[7]	Review of PV systems	General robotics / energy harvesting	PV-based energy harvesting	Various	Comprehensive overview of PV integration and energy management	Mostly theoretical, limited experimental robotics data
[8]	Multipurpose agricultural robot	Irrigation, seeding, crop monitoring	PV + battery	Wheeled, Bluetooth/Android control	Real-world integration with IoT & solar harvesting	Short-term testing, limited terrain adaptability
[9]	RC autonomous robot	Educational / experimental	PV + battery	Wheeled	Demonstrated low-cost solar-powered operation	No long-duration field validation
[10]	Smart farming robot	Multi-purpose precision agriculture	PV + battery	Wheeled	Integration with IoT and computer vision for energy-aware operation	Tested in controlled field plots; scalability unclear
[11]	RaccoonBot	Environmental monitoring	PV panels + tracking	Wire-traversing robot	Autonomous solar tracking, persistent monitoring	Complex setup, high-cost, not general-purpose

Table I: Summary of Relevant Research

3. System Architecture. - In this section, the system-level architecture of the proposed solar-powered mobile robot designed to operate in territories varying in topology is introduced. The architectures incorporate integration in renewable energy harvesting, power, mobility, and wireless communication. In contrast to architectures designed to optimize each functional component, this proposed architecture is designed to work together in real-world conditions, where renewable energy availability, topographic variation, and wireless communication are interrelated.

Figure I shows how the energy subsystem, control and communication subsystem, and locomotion subsystem are interlinked for this system. Table II show the hardware specification of the prototype

Subsystem	Parameter	Specification / Value
PV Panel	Rated Power	50 W
	Area	0.35 m²
	Mounting Angle	30° tilt adjustable
	Controller	MPPT Solar Charge Controller, 12 V
Battery	Chemistry	$LiFePO_4$
	Nominal Voltage	12 V
	Capacity	12 Ah
	Maximum Continuous Discharge	10 A
	Internal Resistance	50 mΩ
	C-Rate	1 C
Mobility / Drive	Robot Mass	7 kg (including PV, battery, payload)
	Wheel Diameter	0.15 m
	Ground Clearance	0.08 m
	Gear Ratio	1:20
	Motors	4 × DC brushed, 24 W nominal, 12 V
	ESC	4 × 12 V, 15 A
	Max Torque per Motor	0.8 Nm

Sensors / Navigation	Wheel Encoders	500 CPR optical encoders
	IMU	9-axis MEMS (gyro, accel, magnetometer)
	GPS	1 Hz, horizontal accuracy ±2 m
Thermal Monitoring	Contact Thermometers	3 × PT100 sensors on motors and ESC
	Sampling Frequency	1 Hz
Communications	Bluetooth Module	HC-05, 9600 baud, SPP protocol
	Video Streaming	720p, 5 Mbps, Wi-Fi 2.4 GHz
Payload / Other	Maximum Payload	2 kg
	Total System Dimensions	0.45 m × 0.35 m × 0.25 m

Table II: Hardware Specifications

3.1 System Configuration. - The robotic platform is divided into three strongly integrated systems:

- Renewable energy and power management subsystem
- Control and communication subsystem
- Locomotion and Mechanical Subsystem

These systems run simultaneously for the purpose of constant monitoring of the outdoors. Solar power is harnessed for storing in the onboard battery bank, which in turn provides controlled power for the control electronics, motor drivers, and peripheral sensing devices. The Arduino Mega 2560 [12] acts as the main controlling system for the platform, controlling the execution of motion, monitoring, and safe handling of the system. The wireless communication module allows for low-latency command & feedback transmissions.

3.2 Renewable Energy and Power Management Subsystem. - The basis of the control system is an Arduino Mega 2560 microcontroller, which was selected because of more than one serial interface and the possibility of real-time control. This microcontroller executes all the motion instructions, detects the level of battery voltages, sets the conditions for safety, and interacts with all the other peripheral devices.

A dual wireless communication system is used to segregate the motion control and video streaming. The Bluetooth device HC-05 [13] is used to transmit the control commands through a smartphone-based application with lower latency, and a Wi-Fi IP camera is used for streaming videos. This approach allows for independence in motion control and video streaming; hence the system is less prone to interference. Such relay driver circuits are included using 2N2222 transistors [14] to connect the Arduino lower outputs to motor control paths at higher currents, thereby saving the microcontroller from undergoing motor-damaging currents.

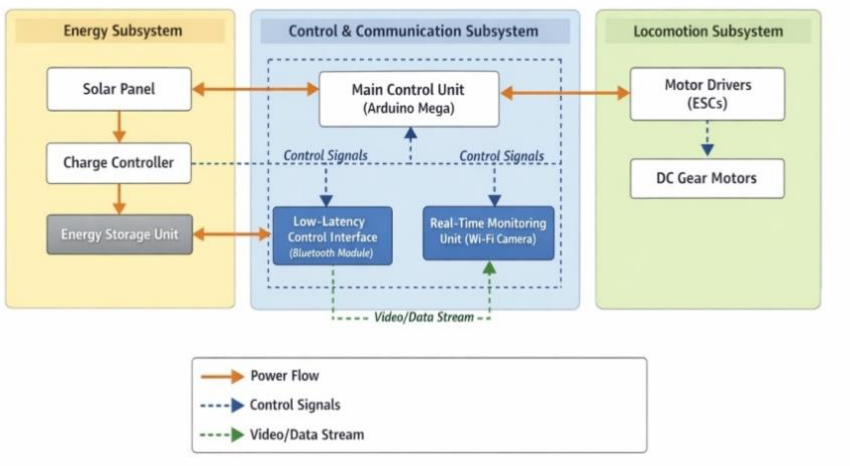

Figure I. System Block Diagram

3.3 Locomotion and Mechanical Subsystem. - The locomotion system comprises four DC gear motors with high torque. The four motors can move through a four-wheel drive mechanism. Each motor is coupled to an electronic speed controller. In this way, a constant torque is created. The four-wheel drive feature allows the robot to move effectively on grass, gravel, or untrenched soil.

The mechanical design consists of a modular PVC chassis, whose material of choice was determined by its ability to be corrosion-resistant, an electrical insulator, easy to work with, and lightweight at the same time. The solar panels, battery bank, motors, and control units are mounted inside the chassis, whose design makes its center of gravity very low to ensure stability of the entire unit while moving on slopes.

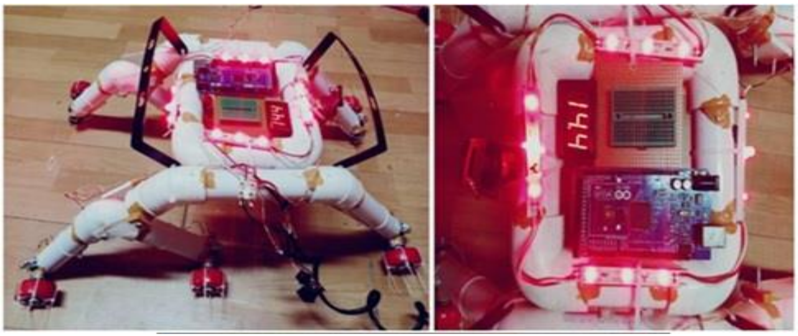

Figure II. Assembled Prototype

3.4 System Integration and Operational Flow. - Solar energy, in the operation stage, is continuously being tapped and supplied either directly to the load or stored within the battery bank, depending on the availability and demand. In the start-up stage, the Arduino initialises all the peripherals, checks the voltage levels at the batteries, and sets up wireless communication. The motion signals commanded from Bluetooth get converted into pulse-width modulation (PWM) signals to command electronic stability control (ESCs) and motors.

While doing so, it also has the ability to do live video transmission via Wi-Fi connectivity. Along with this, the situational awareness for navigation is also facilitated via this feature. The safety feature serves the purpose of constant monitoring of the communications integrity as well as the level of voltage. If the critical threshold is achieved, the system is switched to either safety mode or standby.

4. Methodology. - The methodological framework adopted in the present investigation is intended to experimentally assess the system performance of the solar-powered mobile robot. The emphasis is on the system-level performance, such as energy consumption, energy generation, terrain-based locomotion, communication, and thermal stability.

All experiments are performed outdoors to simulate the combined effects of environmental variability, terrain, and solar energy availability. The experiments are performed under clear to partly cloudy conditions, with an ambient temperature ranging from 18 °C to 32 °C and solar irradiance ranging from 550 W/m² to 950 W/m², as measured using a handheld solar irradiance meter.

4.1 Energy Measurement and Mission Profile. - Energy autonomy is defined as the ability of the robot to maintain operation using the harvested solar power, without the need to recharge the battery from an external source. Battery voltage levels (between 11.9 and 12.6 V) are monitored as an indicator of SOC, but the results are based on the amount of harvested vs. consumed energy in units of Wh rather than SOC.

A standardized mission cycle was defined:

1. Idle state, i.e., the controller and the camera are turned on (5 min)
2. Active locomotion, i.e., moving over the terrain (15 min)
3. Video streaming, i.e., sending data via Wi-Fi (15 min)
4. Solar-assisted charging, i.e., recharging phase (15 min)

The above mission cycle is repeated five times, considering the changing environment, and the results are averaged. The results were obtained from calibrated sensors.

Energy measurements were obtained from calibrated sensors:

- PV input (V_{pv}, I_{pv}) – ±0.5 % accuracy, 1 Hz sampling
- Battery current (I_{bat}) – ±0.5 % accuracy, 1 Hz sampling

Power was integrated over time to compute energy in Wh:

$$E = \sum_{k=1}^{n} P(t_k) \Delta t \quad \text{Eq (1)}$$

where Δt is the sampling interval. The uncertainty in the measurements is expressed as the average value ± standard deviation over multiple measurements. To ensure physical consistency and auditability in the evaluation of the system's performance, the energy generated and the energy consumed have been determined and expressed as energy in Watt-hours (Wh) by calculating the time integral of the measured electrical signal.
The instantaneous power generated by the solar panels is calculated as:

$$Ppv\ (t) = Vpv\ (t) * Ipv\ (t) \quad \text{Eq (2)}$$

where, $Vpv\ (t)$ and $Ipv\ (t)$ are the voltage and current generated by the solar panels, respectively. In the same way, the power being consumed by the system is determined as:

$$Pcons\ (t) = Vbat\ (t) * ILoad\ (t) \quad \text{Eq (3)}$$

The net energy balance in the system is determined as:

$$Enet = EHarvested - EConsumed \quad \text{Eq (4)}$$

The state of charge of the battery, i.e., battery SOC, has been estimated from voltage measurements within the range of 11.9 V to 12.6 V. Yet, since the SOC estimation based on voltage under load conditions depends on the internal battery resistance, it is only used qualitatively rather than quantitatively in the evaluation of the battery.

The uncertainty in the measurements results from the accuracy of the sensors, as well as the environmental conditions, but since the experiments are performed several times, the results are averaged.

4.2 Energy Storage Estimation. - The nominal estimation of the stored energy within the battery system was obtained as follows:

$$Ebat = Vbat \times Cbat \quad \text{Eq (5)}$$

Here, $Vbat$ is the battery voltage, and $Cbat$ is the capacity rating, expressed in ampere-hours. This is the theoretical calculation, but the practical evaluation is done based on the power flow during operation.

4.3 Locomotion Performance Evaluation. - The locomotion performance of the robot was tested on various terrains such as grass, gravel, and dirt. The test was conducted on dry surfaces with a maximum slope of 15 degrees. Various parameters of the locomotion performance of the robot are speed, wheel slip, torque, turn radius, and vibration/acceleration level. To find the average linear velocity of the robot, a sensor fusion technique was used with the help of wheel encoders, a 9-axis IMU, and GPS. The values are sampled at a frequency of 50 Hz. To reduce the noise in the measurement values, a low-pass Butterworth filter with a cutoff frequency of 5 Hz was applied. To find the speed of the robot, the values are calculated over a fixed distance and then averaged out of five iterations.

Wheel slip (%) of the robot was calculated by finding the percentage deviation between the expected distance calculated by the wheel's angular velocity and the actual distance traveled by the robot on the surface using the sensor fusion technique of GPS and IMU. On the gravel surface, the wheel slip was found to be up to 12%, while on the grass and dirt surfaces, the wheel slip was negligible.

Motor torque τ was calculated using:

$$\tau = P\text{mech} / \omega \quad \text{Eq (6)}$$

where Pmech is the mechanical power calculated from the input electrical power, corrected using an 85% drivetrain efficiency estimate, and ω is the angular velocity measured using the encoder. The above equation gives an estimation of the torque requirement over different types of terrain. The peak accelerations are measured using the onboard 9-axis IMU, operating at 50 Hz, and filtered using a low-pass filter to remove noise. The peak levels of vibration, 2.5g, are measured on uneven terrain, and the levels are high on gravel terrain.

4.4 Wireless Communication Evaluation. - The performance of the wireless communication system was tested using a dual-channel communication system, which included Bluetooth control and Wi-Fi video streaming.

For Bluetooth control, the latency (<100 ms) was tested using time-stamped control commands, which were transmitted over ≥5 trials, achieving 10-15 m range, allowing near-real-time control. Video streaming was done using the V380 Pro App, transmitting 1080p, 25 fps, 5 Mbps, using Wi-Fi 2.4 GHz. The latency of the video ranged from 0.5 to 1.5 seconds, while the variations in the quality are due to signal strength, distance (30-50 m), and environment interference.

4.5 Thermal Performance Evaluation. - Temperature readings were obtained through the use of PT100 contact thermometers, which are attached directly to the motor casing, ESC, and battery surface, ensuring good contact through thermal paste. The sampling rate was 1 Hz, and the ambient environment was maintained at a range of 18-32°C. The readings are recorded continuously throughout each experiment.

4.6 Terrain Characterization. - The experimental terrains were classified in order to study the effect of surface properties on robot performance. Three terrain types were considered:

- Grass: moderately compliant surface with good traction and low rolling resistance.
- Gravel: loose particles with higher rolling resistance, higher wheel slip (up to 12%), and uneven surface roughness.
- Dirt: compact soil with stable traction and minimal surface compliance.

All experiments were performed in dry conditions, and the slope was varied from 0° to 15° to assess the robot's locomotion over inclined surfaces. The surface roughness and compliance are also noted qualitatively. The environmental conditions, such as the ambient temperature (18–32 °C) and solar irradiance (550–950 W/m²), are also recorded to assess the energy harvesting and locomotion performance. The classification of the terrains, along with the slope, provides an repeatable method to assess the robot's performance, as indicated by parameters such as speed, torque, and slip, as well as the vibration. Figure III shows the system flow diagram for the proposed system with the experiments performed in the above cycles.

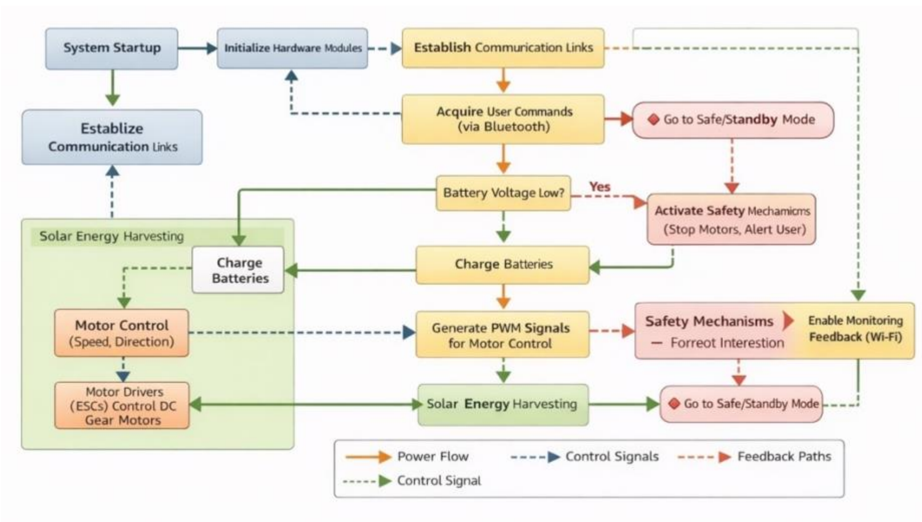

Figure III. System flow chart

5. Results. - Field experiments have been conducted to verify the capabilities of the robot in terms of its locomotion, efficiency of energy consumption, thermal properties, wireless communication, and battery charging/discharging. The experiments have been conducted on grass, gravel, earth, and rough terrain with slopes up to 15° in Karachi, Pakistan.

5.1 Energy Consumption& Thermal Characteristics. - The power consumption of the system was evaluated at three modes of operation: idle mode, locomotion mode, and video streaming mode. From Fig IV and Table III, it can be observed that the system consumed around 5 W of power during the idle mode of operation due to the controller and the camera subsystems. During the locomotion mode on flat surfaces, the system consumed on an average around 34.5 W of power, which translates into an energy consumption of 11.5 Wh during a 20-minute interval. During the locomotion mode on gravel surfaces, the system consumed around 44.5 W of power due to the rolling resistance and wheel slips of the system, which translates into an energy consumption of 11.1 Wh during a 15-minute interval. During the video streaming mode of operation, the system consumed around 6.5 W of power, which translates into an energy consumption of 3.3 Wh during a 30-minute interval.

The thermal measurement results, as shown in Fig. V, indicate that the DC motor was subjected to an average temperature of 45 °C, with a maximum of 52 °C, while the critical temperature was 73 °C. The ESC was subjected to an average temperature of 42 °C, with a maximum of 47 °C, while the limit was 65 °C. The battery was subjected to a safe range, with an average, maximum, and limit values of 33 °C, 42 °C, and 55 °C, respectively. The placement of the sensor, sampling rate, and ambient environment were monitored for each run.

Mode	Avg Power (W)	Energy Consumed (Wh)
Idle	5.0 ± 0.2	0.42 ± 0.02 (5 min)
Locomotion (Flat)	34.5 ± 1.1	11.5 ± 0.5 (20 min)
Locomotion (Gravel)	44.5 ± 1.3	11.1 ± 0.6 (15 min)
Video Streaming	6.5 ± 0.3	3.3 ± 0.1 (30 min)

Table III. Energy consumption of operational modes

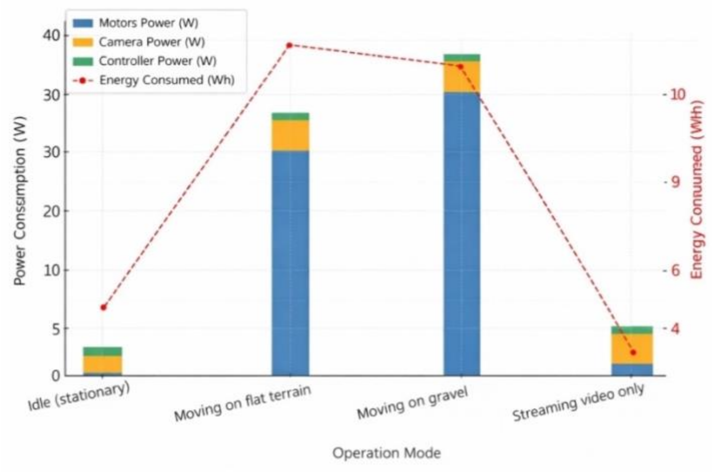

Figure IV. Energy consumption breakdown by operation mode

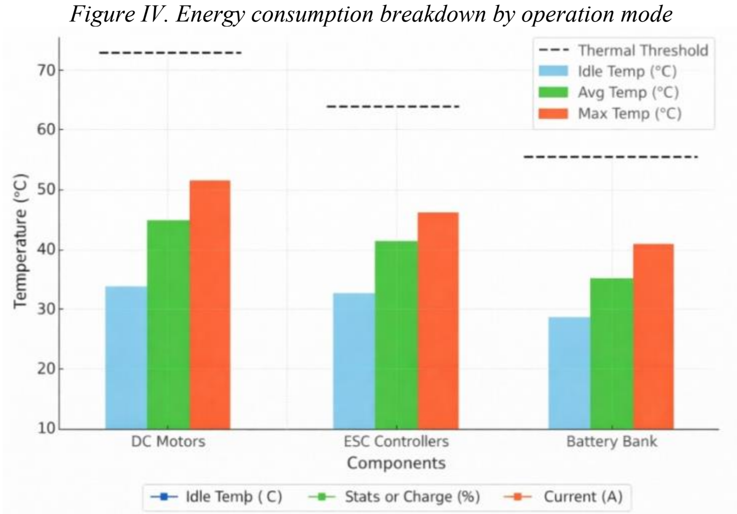

Figure V. Temperature Variation of Components

5.2 Terrain-Dependent Locomotion. - The four-wheel drive robot was able to traverse different types of terrain. The PVC provided the required shock absorption, hence stability on rough terrain. It was also able to climb a 15° slope. Very harsh terrain, such as heavy mud or large rocks, would be a problem, depending on the size of the wheels and ground clearance. The average speeds obtained were 1.0 m/s on gravel, 1.4 m/s on dirt soil, with a turn radius of 0.5 m and a wheel slip of 12% on gravel. The peak acceleration on the rough terrain was 2.5 g. Table IV represents the locomotion performance metrics used.

Metric	Grass	Gravel	Dirt
Avg Speed (m/s)	1.2	1	1.4
Turning Radius (m)	0.5	0.5	0.5
Wheel Slip (%)	3	12	2
Torque (Nm)	0.7	0.9	0.8
Peak Vibration (g)	2	2.5	1.8

Table IV. Locomotion Performance Metrics

It can be seen from Fig VI that gravel terrain causes higher torque, slippage, and hence reduced speeds and inclines, as opposed to grass and dirt terrain that offer better gripping properties and reduced mechanical losses.

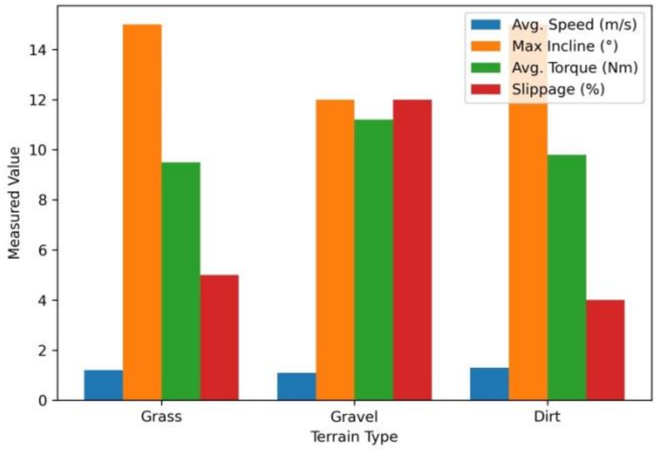

Fig VI. Comparison between the traction and performance parameters on grass, gravel, and dirt track.

5.3 Wireless Communication Performance. - Control via Bluetooth and video transmission through the V380 Pro App (See Fig VII) also performed well. The delay between control commands was less than 100 ms, ensuring near-real-time control, but the delay in video transmission was between 0.5 s and 1.5 s, depending on Wi-Fi network strength. The video was clear at a range of 30 meters in 1080p, but compression was seen beyond 50 meters. Table V. Represents the quality metrics used for remote operation and streaming quality.

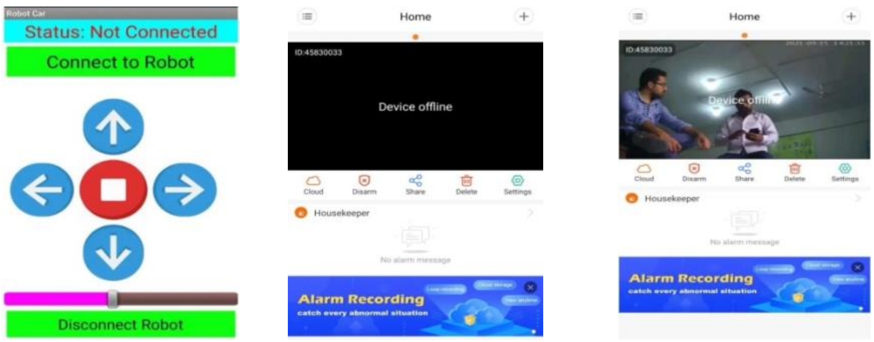

Figure VII. V380 Pro Application Interface

Metric	Value / Observation
Bluetooth Control Latency	< 100 ms
Video Streaming Latency	0.5–1.5 s
Video Quality	1080p HD (≤30 m)
Signal Strength (RSSI)	Bluetooth: -60 dBm; Wi-Fi: -50 dBm
Video Frame Rate	~25 fps
Command Packet Loss Rate	<1%

User Experience Rating	4.5 / 5
Control Operational Range	~15 m
Video Streaming Range	30–50 m

Table V. Remote Operation and Streaming Quality Metrics.

5.4 Battery Charging and Discharge Behavior. - The battery performance was monitored during the continuous outdoor operation. The solar power received from the PV panel can provide a maximum current of 7 A under direct sunshine, as depicted in Fig. VIII. During the active locomotion and video streaming, the battery voltage decreased from 12.6 V, which is the fully charged voltage, to 11.9 V within 30 min. After the solar charging, the voltage returned to 12.6 V, and the SOC returned to approximately 90% within the 50th minute, which indicates the positive energy balance during the mission operation.

The SOC level was also estimated for the battery, based on voltage levels (11.9V-12.6V), and this is only an indicative trend, since there is a level of uncertainty when voltage is used to calculate SOC levels, especially when dynamic load is involved and internal resistance is a factor. Thus, the evaluation is based on the actual harvested and consumed energy (Wh) rather than SOC levels.

This evaluation, based on actual harvested and consumed energy, confirms that the robot is able to sustain its operation on flat, gravel, and dirt terrains without any additional power supply, under the given environmental conditions.

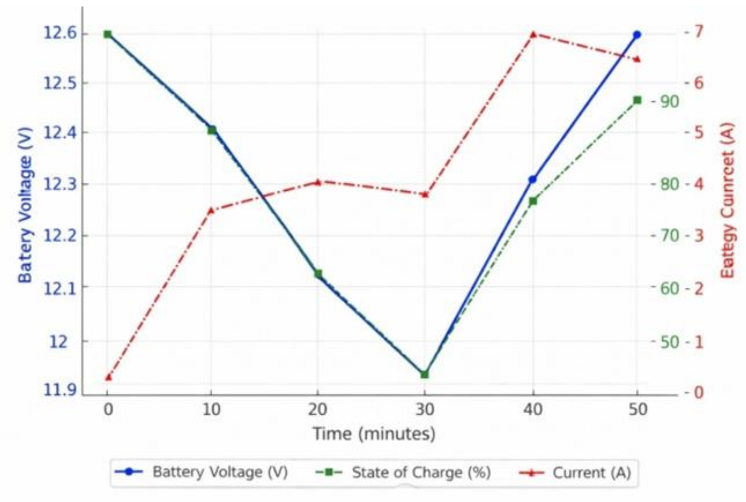

Figure VIII. Battery Performance Over Time

6. Conclusion and Future Directions. - In this paper, the authors have presented a solar-powered, terrain-adaptive mobile robot that integrates energy harvesting, four-wheel drive, dual wireless communication, and passive thermal management into a modular platform. The experimental results have shown the positive energy balance and reliable operation on various types of terrain, indicating the potential of the robot to perform autonomous, off-grid monitoring. There are several areas where the system can be improved. The future work may be focused on the improvement of the energy efficiency of the system using adaptive solar tracking and energy recovery mechanisms, improvement in the adaptability of the robot using advanced suspension mechanisms, and improvement in the communication capabilities using mesh networking techniques. The integration of machine learning techniques to enable the robot to navigate autonomously through the terrain and optimize the energy efficiency, as well as the reduction in the cost of the system using efficient components, will enable the system to be scalable to perform the task in large numbers.

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