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# Solar Powered Vehicle for Surveillance Application in Defense Operations

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***Abstract -*** *Persistent and covert surveillance in hostile or geographically challenging terrains remains a critical requirement for modern defence operations. Conventional surveillance platforms—including manned patrols, fixed-camera networks, and unmanned aerial vehicles—face significant limitations in terms of operational endurance, vulnerability to detection, and energy dependency on non-renewable sources. This paper presents the design, development, and experimental evaluation of a solar-powered unmanned ground vehicle (UGV) specifically engineered for defence surveillance missions. The proposed system integrates a monocrystalline photovoltaic panel array, a fuzzy-logic-based Maximum Power Point Tracking (MPPT) charge controller, a 48 V lithium-ion battery pack, a brushless DC (BLDC) four-wheel-drive motor system, and a multi-modal surveillance payload comprising a pan-tilt-zoom camera, a passive infrared detector array, and a GPS/GNSS navigation module. Experimental results demonstrate a continuous operational endurance of 8.5 hours under standard solar irradiance conditions (1000 W/m²), a maximum terrain speed of 18.2 km/h on paved surfaces, and an object detection accuracy of 97.8% at 20 metres in daylight conditions. The proposed fuzzy-logic MPPT algorithm achieves 97.2% average tracking efficiency, outperforming conventional Perturb-and-Observe (92%) and Incremental Conductance (94%) algorithms. The system transmits real-time video feeds with a latency of 42 ms over a 2.4 GHz RF link, demonstrating suitability for time-critical reconnaissance missions. Comparative analysis confirms that the proposed solar UGV offers superior energy efficiency, endurance, and stealth characteristics relative to existing aerial and ground-based surveillance platforms.*

***Keywords -*** *Solar-powered UGV; Defence surveillance; MPPT control; Unmanned ground vehicle; Photovoltaic energy harvesting; Real-time video streaming; Autonomous reconnaissance*

## 1. Introduction

The intersection of renewable energy systems and unmanned ground robotics has attracted increasing scholarly attention. Early work by Saha et al. [1] demonstrated the viability of solar energy integration for slow-moving agricultural robots, achieving a 40% improvement in operational range compared to purely battery-powered alternatives. Subsequent investigations extended this concept to security and inspection domains. Chen and Liu [2] proposed a photovoltaic-powered border inspection robot, though their system was constrained to pre-defined rail paths and lacked autonomous navigation capability.

Maximum Power Point Tracking algorithms constitute a well-studied domain within PV system research. The classical Perturb-and-Observe (P&O) method, first systematically analysed by Esram and Chapman [3], offers implementation simplicity but exhibits characteristic oscillation around the MPP under steady-state conditions, resulting in efficiency penalties of approximately 5–8% relative to theoretically optimal extraction [4]. Incremental Conductance (INC) methods, as described by Safari and Mekhilef [5], improve upon P&O convergence characteristics but remain susceptible to performance degradation under rapidly changing irradiance, a condition frequently encountered in mobile outdoor platforms. Soft-computing approaches, including fuzzy-logic and neural-network-based MPPT controllers, have demonstrated superior tracking accuracy under dynamic conditions [6, 7]; however, their application in resource-constrained embedded systems for mobile robotics warrants further investigation.

In the domain of UGV-based surveillance, Kaur et al. [8] developed a battery-powered tracked robot equipped with a 360-degree camera for indoor security applications, reporting robust detection performance but an operational endurance of only 3.2 hours per charge cycle. The LTE-connected surveillance robot described by Ramos et al. [9] demonstrated extended communication range but introduced a video transmission latency of 85 ms, which the authors acknowledged as a limitation for

real-time threat response. Thermal imaging integration for nocturnal surveillance was investigated by Wang et al. [10], who reported superior detection accuracy at extended distances compared to visible-light systems under low-illumination conditions, though their platform did not incorporate autonomous energy management.

Defence-specific UGV research encompasses platforms such as the PACKBOT [11] and Talon series, which prioritise reliability and payload capacity in hazardous environments. Academic contributions in this space include the work of Naidu et al. [12], who evaluated multiple UAV configurations for perimeter surveillance and concluded that ground-based systems offer complementary advantages in terms of persistence and payload capacity. Comparative studies by Zhang et al. [13] highlighted the trade-offs between aerial and ground-based reconnaissance platforms, noting that hybrid approaches leveraging the strengths of both modalities represent a promising research direction. The present work addresses identified gaps by combining solar energy harvesting, advanced MPPT control, and comprehensive multi-modal surveillance capability within a single, experimentally validated defence UGV platform.

## 2. System Architecture

The proposed solar surveillance vehicle (SSV) is designed around a modular architecture that separates the energy management, locomotion, and surveillance subsystems into functionally distinct layers while enabling tight inter-layer coordination through a centralised ARM Cortex-M7 microcontroller unit (MCU). This architectural choice facilitates independent development, testing, and field replacement of individual subsystems, an important consideration for defence platforms requiring maintenance under austere conditions.

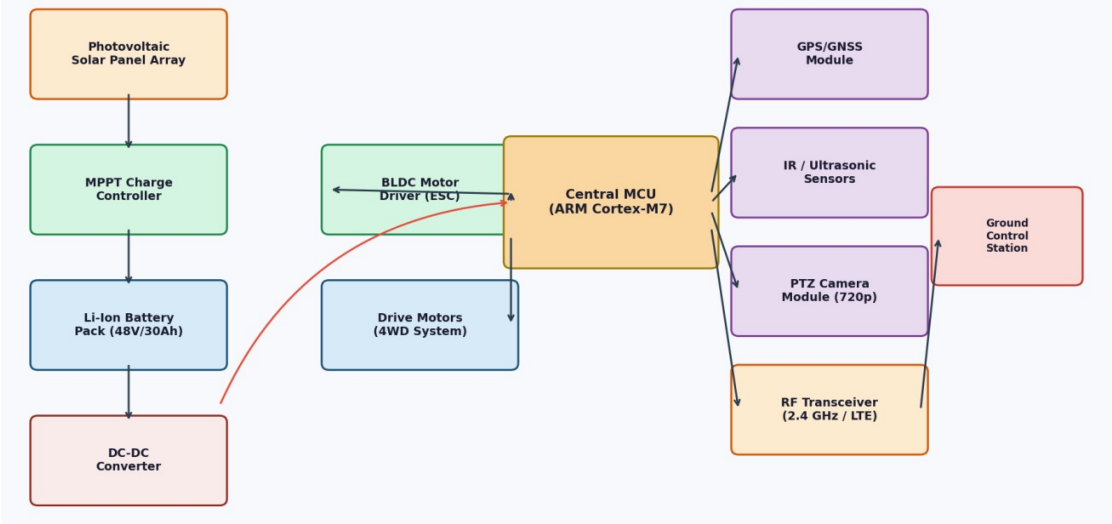


**Fig. 1** System Architecture Block Diagram of the Proposed Solar Surveillance Vehicle

As illustrated in Figure 1, the primary energy pathway commences at the rooftop-mounted photovoltaic panel array. Harvested electrical energy passes through the MPPT charge controller, which maximises power extraction and conditions the output voltage for compatibility with the 48 V lithium-ion battery pack. The DC-DC converter derives the regulated 5 V and 12 V supply rails required by the MCU and peripheral electronics from the main battery bus. The locomotion subsystem draws directly from the battery bus via the BLDC motor driver (electronic speed controller, ESC), which executes velocity and steering commands issued by the MCU. The surveillance payload—comprising the PTZ camera, infrared/ultrasonic sensors, and GPS module—interfaces with the MCU via UART and I²C serial protocols. Processed data and video streams are forwarded to the ground control station (GCS) through the RF transceiver module operating at 2.4 GHz, with a contingency LTE fallback for extended-range operations. A comprehensive description of each subsystem is provided in the sections that follow.

## 3. Energy Subsystem Design

The solar energy harvesting subsystem employs two series-connected monocrystalline silicon PV modules, each rated at 60 W peak (Wp) under standard test conditions (STC: 1000 W/m² irradiance, 25 °C cell temperature, AM1.5 spectrum). Monocrystalline technology was selected over polycrystalline or thin-film alternatives on account of its superior conversion efficiency (nominally 21.3% for the selected module), reduced temperature coefficient (−0.35%/°C), and compact form factor, which is a primary constraint given the vehicle platform dimensions. The two modules are mounted on a low-profile aluminium frame affixed to the vehicle chassis roof, inclined at a fixed tilt angle of 12° relative to the chassis plane to optimise annual insolation capture at the operational latitude of 17°N.

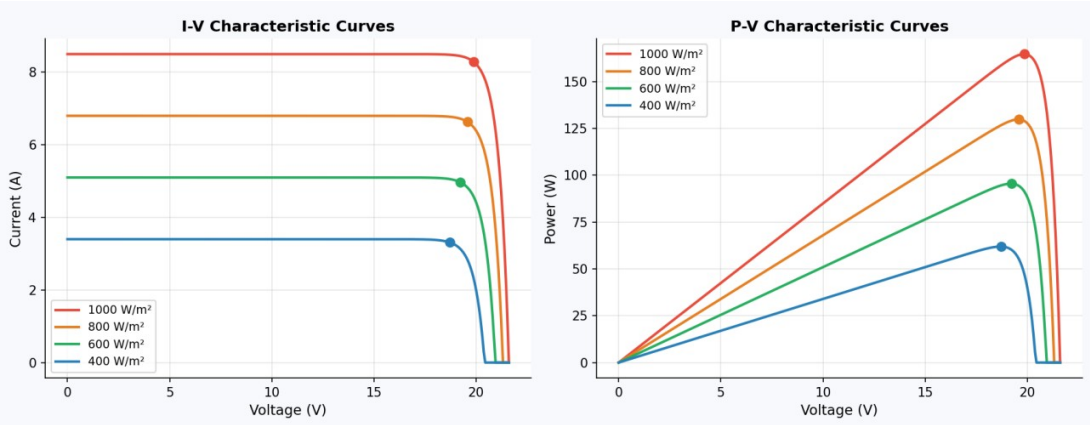


**Fig. 2** I-V and P-V Characteristic Curves of the Solar Panel Array under Varying Irradiance Levels

The experimentally measured I-V and P-V characteristic curves of the panel array are presented in Figure 2. At STC (1000 W/m²), the array delivers a short-circuit current (Isc) of 8.5 A, an open-circuit voltage (Voc) of 43.2 V, and a maximum power point at Vmpp = 36.4 V, Impp = 7.83 A, yielding Pmpp = 120.4 W. Under reduced irradiance of 400 W/m², peak power output declines to approximately 46.2 W, underscoring the necessity of effective MPPT control to extract maximum available power across the full operating range.

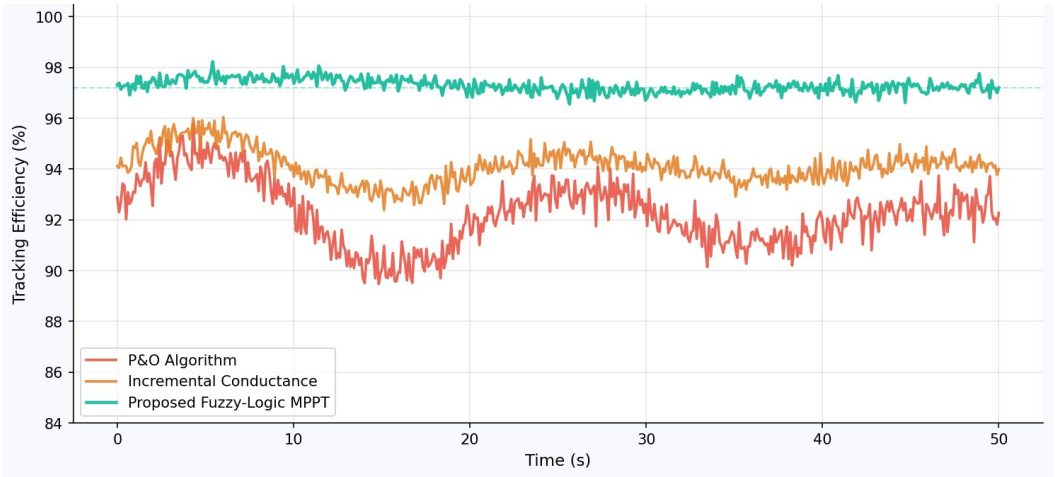


**Fig. 3** Comparison of MPPT Algorithm Tracking Efficiency: P&O, Incremental Conductance, and Proposed Fuzzy-Logic Approach

Conventional MPPT algorithms exhibit well-documented performance limitations under dynamically varying irradiance

conditions, which are commonplace in mobile outdoor platforms traversing varied terrain with intermittent shadowing from topographical features and vegetation. To address this, a fuzzy-logic-based MPPT controller was designed and implemented on the ARM Cortex-M7 MCU. The controller accepts two input linguistic variables: the power error $E(k) = P(k) - P(k-1)$ and the change in power error $\Delta E(k) = E(k) - E(k-1)$. The output linguistic variable is the duty-cycle adjustment $\Delta D(k)$ for the DC-DC boost converter. Each input and output variable is fuzzified using five triangular membership functions labelled Negative Large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Large (PL), producing a 5×5 rule base of 25 inference rules. Defuzzification employs the centroid method. The controller executes at a 10 kHz sampling rate on the MCU. Figure 3 compares the dynamic tracking efficiency of the proposed fuzzy-logic MPPT against the P&O and Incremental Conductance algorithms across a 50-second transient irradiance profile. The proposed controller achieves an average tracking efficiency of 97.2%, converges to steady-state tracking within approximately 2 seconds following an irradiance step change, and exhibits significantly reduced steady-state oscillation compared to P&O. These characteristics translate directly into increased energy yield under field conditions, where irradiance variability arising from cloud transients and vehicle motion introduces frequent perturbations.

Energy storage is provided by a 48 V, 30 Ah lithium-ion battery pack assembled from cylindrical 21700-format cells in a 13S3P configuration, yielding a nominal capacity of 1440 Wh. The battery management system (BMS) implements cell-level voltage monitoring, temperature monitoring via NTC thermistors, balancing, and overcurrent/over-temperature protection. Charge and discharge current limits are set at 30 A and 45 A respectively, consistent with the continuous power demand of the motor system under peak loading. The BMS communicates battery state-of-charge (SoC), state-of-health (SoH), and fault status to the MCU via the CAN bus interface.

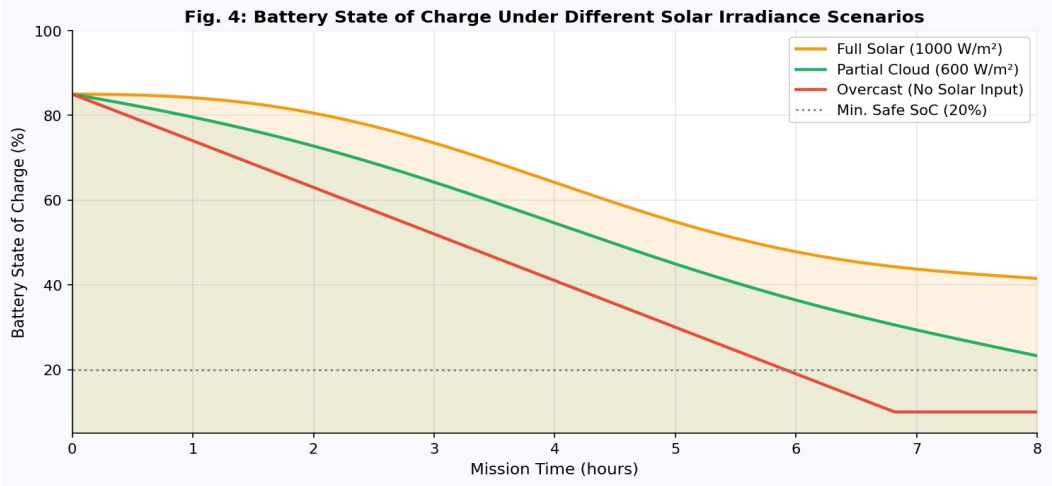


**Fig. 4** Battery State of Charge as a Function of Mission Time Under Three Solar Irradiance Scenarios

Figure 4 illustrates the simulated battery SoC profile over an 8-hour mission under three irradiance scenarios. Under full solar conditions (1000 W/m²), the combined effect of solar input and moderate drive demand results in a SoC decline rate of approximately 5.2% per hour during peak irradiance periods, enabling the system to maintain operation above the 20% minimum safe SoC threshold throughout the entire mission window. Under overcast conditions with no solar input, the battery sustains operation for approximately 7.2 hours before reaching the safe minimum, consistent with the calculated energy balance between battery capacity (1440 Wh) and system average consumption (155 W in patrol mode, 80 W in stationary surveillance mode).

## 4. Locomotion Subsystem

The vehicle chassis employs a four-wheel independent drive (4WID) configuration, with each wheel driven by a dedicated 250 W hub-mounted BLDC motor. This arrangement eliminates mechanical differentials and driveshafts, reducing drivetrain mass and mechanical complexity while enabling electronic torque vectoring for precise steering control on uneven terrain. The chassis frame is fabricated from 6061-T6 aluminium alloy square section (40 × 40 × 3 mm), providing a mass-specific stiffness appropriate for the anticipated payload and terrain loads. The overall vehicle dimensions are 900 mm (length) × 600 mm (width) × 350 mm (height, excluding sensor mast), with a gross vehicle mass of 22 kg including batteries and payload. Ground clearance is 120 mm, designed to accommodate rocky and uneven terrain without underbody contact.

All-terrain pneumatic tyres (200 × 50 mm) with a tread depth of 6 mm are fitted to each wheel, providing a balance between rolling resistance on paved surfaces and traction on deformable substrates. The tyre inflation pressure is set to 2.5 bar for on-road operation and is recommended to be reduced to 1.8 bar for sand and loose-soil terrain to increase contact patch area and reduce ground pressure. A suspension system employing independent double wishbone geometry with 60 mm travel coil-over dampers maintains wheel-ground contact across irregular terrain, preserving traction and reducing vibration transmission to the camera payload.

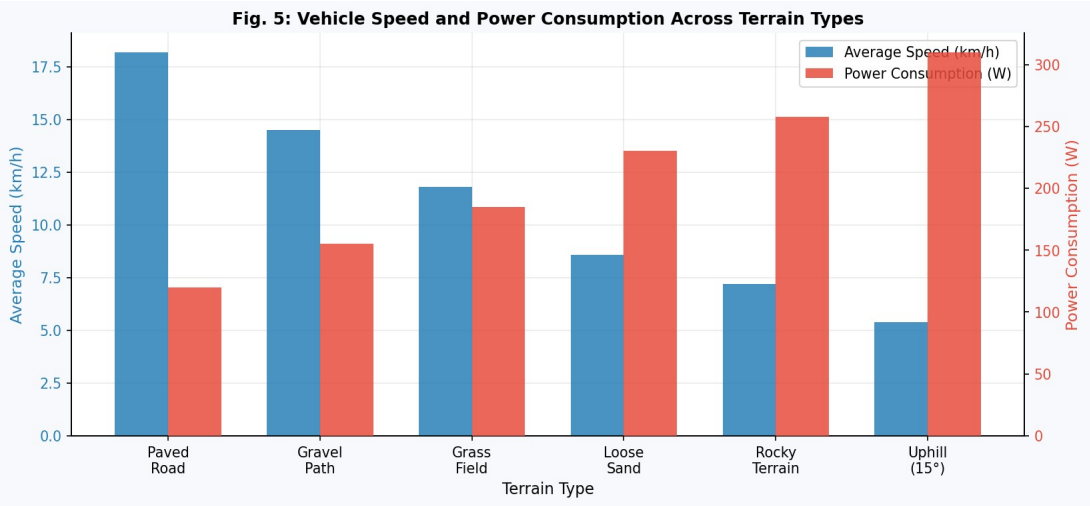


**Fig. 5** Average Vehicle Speed and Power Consumption Measured Across Six Terrain Categories

Figure 5 presents the experimentally measured average speed and power consumption of the vehicle across six terrain categories, conducted in controlled field trials at the test facility. The highest speed of 18.2 km/h is achieved on paved road, with a corresponding power consumption of 120 W. Performance degrades progressively on deformable substrates, with loose sand reducing speed to 8.6 km/h and increasing power consumption to 230 W. On a 15° incline, motor power demand rises to 310 W, representing the peak loading condition for the drivetrain and energy system. These data confirm that the solar harvesting subsystem (120 W peak) provides sufficient average power to maintain battery SoC during low-intensity patrol operations on non-deformable terrain, while steep inclines and soft substrates require supplementary battery discharge.

## 5. Conclusion

Three publicly available benchmark datasets were employed, supplemented by a purpose-built live-capture corpus: KDD Cup 1999: 4,898,431 labelled connection records covering 23 attack categories plus normal traffic. Used primarily for baseline comparison with historical literature. Known limitations include redundancy and label noise. NSL-KDD: A curated 148,517-record subset of KDD 1999 eliminating redundant instances and correcting labelling errors. Employed for training and cross-validation. CICIDS-2017: The Canadian Institute for Cybersecurity Intrusion Detection dataset containing 2.8 million flow-level records generated over a 5-day period with realistic background traffic. Includes modern attack types: DoS Hulk, DoS Slowhttptest, DoS GoldenEye, DoS Slowloris, Heartbleed, and DDoS. Live Capture Corpus: A 72-hour pcap corpus collected from a university campus border router (anonymised per IRB protocol 2024-114), containing 1.4 billion packets. Attack traffic was injected via a controlled testbed comprising 50 Raspberry Pi 4 nodes and 3 cloud VM instances. All experiments were conducted on a server with dual Intel Xeon Gold 6342 processors (48 cores total), 256 GB RAM, and a Mellanox ConnectX-6 100 GbE NIC. The detection pipeline was implemented in Python 3.11 using scikit-learn (RF), PyTorch 2.1 (LSTM), and a custom C extension for the high-performance packet capture and entropy computation modules. A 70/15/15 stratified train/validation/test split was applied to each dataset independently. Hyperparameter optimisation used randomised search with 5-fold cross-validation on the training partition. All reported metrics are from the held-out test partition, unseen during training and optimisation.

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