

Smart Thermal Imaging Drone for Solar Panel Inspection

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Abstract— The increasing significance of renewable energy, particularly solar power, necessitates the development of efficient maintenance strategies for solar panel installations. Conventional inspection methods often lack the precision required to identify subtle anomalies affecting energy production. To address this challenge, a groundbreaking solution in the form of a smart thermal imaging drone is introduced. This project encompasses the design, development, and implementation of a drone equipped with advanced thermal imaging technology, specifically the MLX90640 thermal sensor, for comprehensive solar panel inspection. Integrated with the ESP32 microcontroller, the system facilitates real-time data processing and transmission, enabling timely analysis of thermal data. Furthermore, a 3D-printed protective housing ensures the durability and resilience of the system in various environmental conditions. Through field tests conducted at MAHSA University, the effectiveness of the smart thermal imaging drone in detecting temperature differentials and anomalies on solar panels has been demonstrated. The system's versatility and mobility enable efficient coverage of large solar panel arrays, facilitating proactive maintenance and optimization efforts. By revolutionizing solar panel inspection through the fusion of aerial mobility and thermal imaging technology, this project aims to enhance the efficiency, accuracy, and cost-effectiveness of solar energy production, contributing to a sustainable energy future.

Keywords— *Photovoltaic (PV), Thermal Camera (MLX90640), Charging Module (TP4056), Mini Drone (S8S), Polylactic Acid (PLA), lithium-Polymer (LIPO), Inspection, Faulty Cell, Solar panel.*

I. INTRODUCTION

This introduction delineates the pressing necessity for rigorous solar panel inspection methodologies to optimize energy yield, positioning solar power as a cornerstone of the global shift towards sustainability. Essential to the efficacy of solar energy is the maintenance of solar panel integrity, yet prevailing inspection methods frequently falter in discerning nuanced anomalies, potentially leading to energy losses and operational inefficiencies. To remedy these shortcomings, this project proposes a transformative solution: the development of a smart thermal imaging drone tailored explicitly for solar panel inspection. By integrating state-of-the-art technologies such as the MLX90640 thermal sensor and the ESP32 microcontroller, this drone system aims to redefine solar panel diagnostics. The adoption of thermal imaging technology enables a non-invasive approach to detecting temperature variations on solar panels, facilitating the identification of hotspots and irregularities that may impede energy production. Furthermore, the aerial mobility of the drone affords comprehensive coverage of

expansive solar panel arrays, overcoming limitations associated with ground-based inspection methodologies [1].

The utilization of drones for various industries, including solar energy, began to gain traction in the early 2000s. Drones were initially used for aerial photography and surveying, but their potential for solar panel inspections quickly became evident. In 2010, thermal imaging technology became more accessible and affordable, enabling the integration of thermal cameras with drones. These thermal imaging systems proved invaluable in identifying temperature differences on solar panels, facilitating inspections for hotspots, faulty connections, and damaged cells. Moreover, advancements in drone technology during this time made them more compact, lightweight, and maneuverable. Longer flight times, improved battery life, and advanced flight control systems enhanced the efficiency and capabilities of thermal drones for solar panel inspections. Data analysis software was also developed to manage and interpret the vast amounts of thermal imagery collected during inspections [2].

Solar panels frequently encounter heating issues, necessitating laborious and hazardous manual inspections. Traditional methods, such as ground-based inspections, are limited in coverage and prone to inaccuracies, resulting in prolonged processes and human errors [3]. To address this challenge, a thermal imaging drone system is proposed for efficient inspection. However, challenges like weather conditions and flight restrictions may hinder effectiveness. This study aims to mitigate these limitations, advancing thermal drone technology for solar panel inspections to enhance efficiency, accuracy, and safety while promoting proactive maintenance in the solar energy industry. By streamlining inspection processes and minimizing risks, this innovative approach seeks to optimize solar panel performance and contribute to the sustainability of renewable energy systems, thereby fostering a greener and more resilient future.

II. METHODOLOGY

Developing smart thermal imaging drone which involves the design and integration of an MLX90640 thermal camera onto the S8S drone. The primary aim is to enable the drone to autonomously capture thermal images of solar panels, facilitating efficient inspection processes. The methodology covers a spectrum of critical steps including the selection of the appropriate components, the intricacies of hardware integration, the intricacies of software programming for autonomous operations, advanced data analysis techniques, and robust validation procedures. This methodical approach is crucial for the successful deployment of this innovative

thermal imaging drone system, specifically optimized for solar panel inspections. Fig 1 presented the hardware element involves in the system.

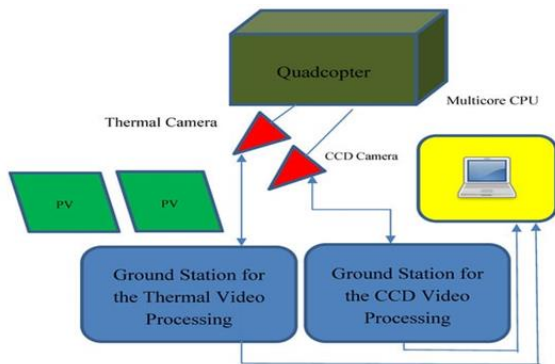


Fig. 1. System description highlighting key hardware elements

A. Hardware Integration

The hardware integration phase encompasses a meticulous process aimed at seamlessly incorporating the MLX90640 thermal camera onto the S8S Mini drone as presented in Fig 2. This critical stage involves a comprehensive examination of specific components, tools, and procedural steps essential for successful integration. Key considerations include ensuring compatibility between the thermal camera and drone hardware, selecting appropriate mounting hardware to securely affix the camera onto the drone frame, and establishing reliable electrical connections to power and interface the camera with the drone's onboard systems. Additionally, the integration process may entail custom modifications to the drone's structure to accommodate the additional payload and optimize overall aerodynamic performance. Rigorous testing and calibration procedures are also integral to verifying the functionality and performance of the integrated system, ensuring seamless operation and precise thermal imaging capabilities during drone missions. Through meticulous planning, execution, and validation, the hardware integration phase serves as a foundational step towards realizing a fully operational smart thermal imaging drone for solar panel inspection applications.

In addition to the MLX90640 thermal camera, several other components play crucial roles in the hardware integration phase. The 3D Camera Enclosure or Housing provides protection and stability for the camera, shielding it from external elements such as dust and moisture. The TP4056 Charging Module acts as a charging management system for the LiPo battery, ensuring safe charging and optimal battery performance. The 3.7V, 1000mAh LiPo Battery serves as the primary power source for the drone system, supplying electrical energy for the thermal camera and onboard systems. The Switch controls the power flow to the drone system, allowing users to turn the power on or off as needed, enhancing user control and facilitating power conservation. Together, these components play crucial roles in the successful integration of the thermal imaging system onto the drone platform, enabling efficient and reliable operation for solar panel inspection missions.



Fig. 2. MLX90640 and S8S Mini drone.

The successful integration of the MLX90640 thermal camera onto the S8S drone as presented hinges on careful consideration of its physical characteristics. The compact dimensions of the MLX90640, measuring approximately 11.5 x 15 x 5.7 mm (0.45 x 0.59 x 0.22 inches), enable a seamless and stable placement on the drone platform without causing significant imbalance or disruption to the drone's flight dynamics. Additionally, the lightweight nature of the MLX90640, weighing around 4 grams (0.14 oz), ensures minimal impact on the drone's payload capacity and overall flight performance. It is imperative to select an appropriate mounting location for the MLX90640 thermal camera to prevent interference with the S8S drone's aerodynamics and weight distribution. While the addition of the thermal camera may have a minor influence on the drone's aerodynamics, this impact should be evaluated to safeguard the drone's flight performance. Furthermore, the MLX90640 thermal camera will have its own power system consisting of an 800mAh LiPo battery, TP4056 charger, and a switch button. The integration of this power system should be executed carefully to ensure a harmonious operation with the S8S drone. The impact of the thermal camera's power consumption on the LiPo battery's life should be thoroughly assessed to guarantee that the drone maintains sufficient battery capacity for the intended mission.

B. Software Development

The software development phase of the solar panel inspection system, incorporating the MLX90640 thermal camera atop the S8S drone, utilizes Arduino IDE for programming the ESP32 microcontroller and JavaScript for web-based functionalities. Firebase serves as the cloud-based database and storage solution for storing thermal images and facilitating real-time data exchange between the drone and the user interface. The software architecture is designed with several modules responsible for tasks such as data acquisition, processing, user interface development, and communication. HTML, CSS, and JavaScript are employed to create a responsive and interactive web-based control panel for the drone system. The software interfaces with the thermal camera to capture images, processes them for visualization and anomaly detection, and streams live thermal imagery to the user interface. Captured thermal images are securely stored in Firebase for easy access and management. The control flow presented in Fig 3 involves initializing components, continuous image capture, data processing, broadcasting, and client interaction via a WebSocket server, ensuring uninterrupted operation of the system for efficient solar panel inspection.

In addition to facilitating real-time data exchange between the drone and the user interface, the software development phase includes the implementation of specific functionalities to enhance the inspection process as presented in Fig 4. The Arduino code programmed for the ESP32 microcontroller enables seamless communication with the MLX90640 thermal camera, ensuring precise data acquisition. JavaScript functions within the web-based control panel enable dynamic visualization of thermal imagery, allowing users to adjust display settings and interact with captured images effectively. Furthermore, Firebase serves as a centralized repository for storing captured thermal images, providing users with easy access to inspection data for analysis and decision-making purposes. The control flow within the software architecture ensures continuous operation of the system, from initialization to client interaction, thereby optimizing the efficiency and reliability of solar panel inspection missions. Through meticulous integration and development efforts, the software components synergize to form a robust and user-friendly platform for conducting thermal inspections of solar panels.

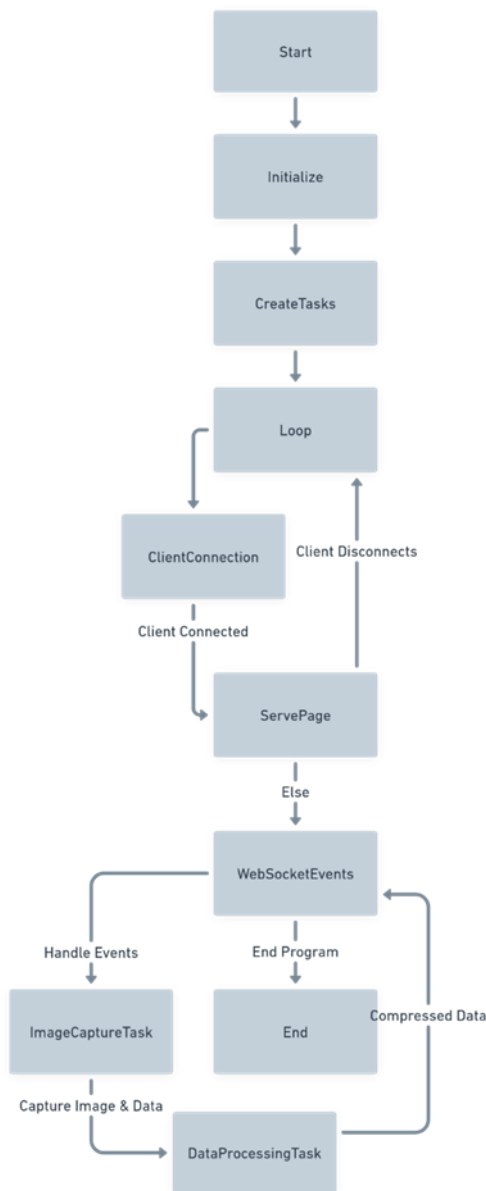


Fig. 3. Control flow and data interactions of MLX90640.

C. Data Analysis Techniques

The thermal camera code utilizes several image processing techniques in JavaScript to transform raw data into a visually informative heatmap. These techniques ensure efficient data handling, smoother visualizations, and accurate temperature representation. Data Decompression is the compressed data received from the server is processed by the decompress function. This function employs a clever combination of numeric multipliers and letter codes to represent temperature values efficiently. Numeric multipliers indicate how often the next letter code value should be repeated, compressing similar temperature readings. Represent actual temperature values with positive values encoded as uppercase and negative values as lowercase. The function decodes this cryptic language, reconstructing the original temperature readings from the compressed string [4]. Data Interpolation is the interpolate data function takes the decompressed temperature values and "fills in the gaps" between them. This process estimates additional temperature points, creating a smoother heatmap. By calculating the average between neighboring pixels, the function generates intermediary values that provide a more nuanced representation of the thermal image [5].

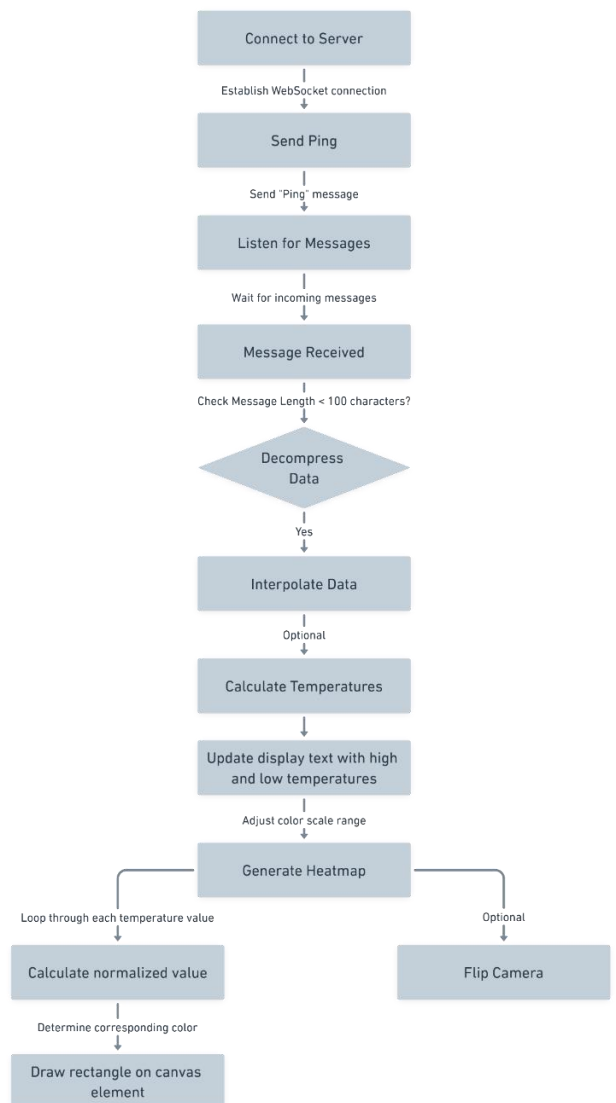


Fig. 4. JavaScript and image processing techniques.

Temperature Calculations used to gain a broader understanding of the thermal data, the code calculates the average high and low temperatures. It sorts the decompressed values and extracts the middle portion as the "typical" temperature range. This provides a concise statistical summary of the overall thermal landscape captured by the camera [6]. Heatmap color for value function translates temperature values into colors for the heatmap visualization. This function utilizes a temperature-to-color mapping algorithm, assigning specific hues and saturations based on the intensity of the temperature reading. Cooler temperatures generally map to shades of blue and green, while hotter areas are represented by yellows, oranges, and reds. This intuitive color mapping allows users to quickly grasp the temperature variations within the image [7].

III. RESULT AND DISCUSSIONS

The proposed smart thermal imaging drone system for solar power inspection was implemented by integrating the MLX90640 thermal sensor with an ESP32 microcontroller presented in Fig 5. The live thermal imaging stream was successfully transmitted to a webpage using a combination of Arduino IDE and HTML/JavaScript code. The image processing algorithm applied in real-time converted the thermal data into a heatmap for enhanced visualization. The incorporation of a thermal camera, following initial technical challenges, allowed for the successful display of thermal imaging. The use of a TP4056 charging module, coupled with a 1000mAh LiPo battery, ensured a reliable power source for up to 3 hours of continuous operation. The addition of a switch provided a mechanism for toggling between low power mode and full power mode, facilitating efficient charging while the device is inactive.



Fig. 5. Smart thermal imaging drone.

The field tests conducted at MAHSA University aimed to comprehensively assess the performance and efficacy of the smart thermal imaging drone system under diverse operational scenarios. Therefore, the drone was stable and the weight of the thermal camera did not affect on the flight operation.

A. Initial Test Scenario: Normal and Thermal Imaging

In the first test scenario, the system underwent scrutiny in a typical solar panel operating environment. The thermal imaging capability of the MLX90640 sensor, integrated into the drone system, facilitated the capture of not only standard

images but also thermal data revealing nuanced temperature differentials across the solar panel array. The thermal images not only identified hotspot areas, indicative of potential issues such as localized overheating or malfunctioning components, but also presented a quantitative representation of temperature variations. The thermal imaging data reveals elevated temperatures on the right side of the solar panel, while comparatively lower temperatures are observed on the left side. Fig 6 shows the result of the initial test with CCD camera vs Thermal Camera.

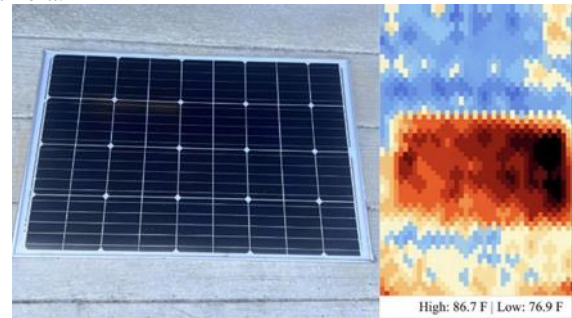


Fig. 6. Initial test with CCD camera vs Thermal Camera.

B. Subsequent Test Scenario: Shadow Introduction

In the second test scenario, a book covers strategically placed over portions of the solar panel array created controlled shadows. The system exhibited a remarkable ability to detect and highlight not only colder areas but also temperature gradients associated with the presence of shadows. The thermal images, in this context, showcased the contrast between the shadowed and non-shadowed regions, elucidating the extent of temperature differentials induced by the introduced shadows.



Fig. 7. Subsequent test for shadow case.

The thermal camera's capability to capture both high and low-temperature extremes became particularly evident during this scenario. The system not only identified colder areas in the shadows but also provided a detailed thermal perspective, showcasing the dynamic temperature changes across the entire solar panel array [8]. Fig 7 shows the result of the subsequent test for shadow case.

C. Final Test Scenario: Varying height

The comprehensive analysis of thermal images acquired by the smart drone system at varying distances, specifically 1.5m, 2m, and 3m, provides crucial insights into the nuances of temperature distribution across the solar panel. Each distance setting serves as a distinctive vantage point, influencing the system's ability to capture and interpret thermal data accurately.

The thermal images presented in this figure depict the solar panel utilized for testing purposes. The analysis captures the solar panel's thermal characteristics under controlled conditions at distances of 1.5m, 2m, and 3m from the smart drone system. The varying distances offer distinct perspectives on temperature distribution, providing valuable insights into the system's performance in capturing thermal anomalies and facilitating a comprehensive assessment of the solar panel's operational status. Fig 8 shows the thermal images at various distance.

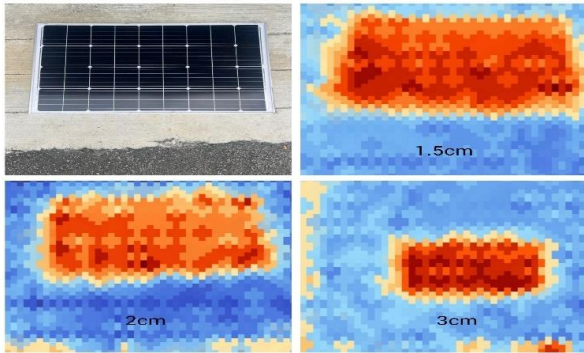


Fig. 8. Thermal images at various distances.

D. Circuit Diagram

The incorporation of a switch within the circuitry introduced dynamic functionality, allowing the device to seamlessly transition between low power mode and full power mode. This feature was designed to optimize energy consumption during periods of inactivity, promoting efficient charging while maintaining the device's operational readiness. The successful integration of these power management features, coupled with the flexibility of Type-C charging as presented in Fig 9 contributes significantly to the system's overall reliability and user convenience [9].

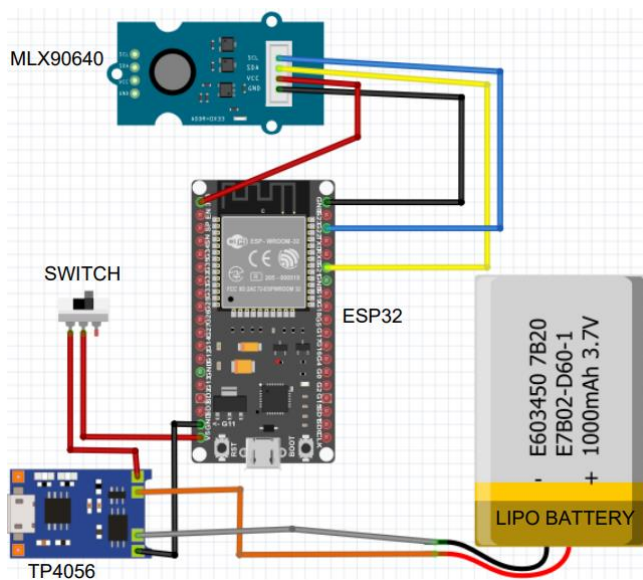


Fig. 9. The proposed circuit diagram

E. Camera enclosure design and Integration

The circuit design was meticulously crafted using Fritzing software to visualize and optimize the integration of components. The 3D-printed camera enclosure, designed to encapsulate the circuitry and camera components, was strategically positioned atop the S8S mini drone as presented in Fig 10. This placement not only safeguarded the components against adverse weather conditions and sunlight but also ensured a lightweight and aerodynamic configuration for the drone.

The S8S drone's capacity to carry additional weight remains an unconfirmed specification by the manufacturer. However, based on an analysis of its technical features, particularly the inclusion of powerful brushless motors and a slightly larger frame compared to similar models, an estimated payload range of 70 grams can be proposed [10]. This range acknowledges the potential for the drone to handle closer to 70 grams due to the enhanced motor capabilities. This estimated payload capacity suggests the S8S's suitability for carrying lightweight payloads such as thermal cameras, lightweight phone mounts, or other compact gadgets. Fig 11 presented the weight of the camera enclosure.

In the fabrication of the protective housing for the smart thermal imaging drone system, Polylactic Acid (PLA) was chosen as the primary material for 3D printing. PLA is a biodegradable and bioactive thermoplastic derived from renewable resources such as corn starch or sugarcane. This selection aligns with environmentally conscious practices, offering a sustainable solution for the manufacturing of components. PLA is renowned for its ease of use in 3D printing, showcasing excellent print quality and minimal warping during the printing process. The material's biocompatibility and lack of toxic byproducts make it suitable for applications where contact with the environment or living organisms is anticipated.

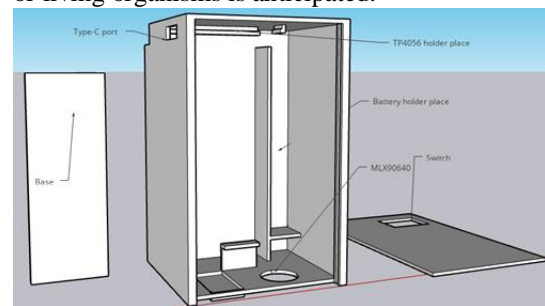


Fig. 10. Sketchup of camera enclosure.

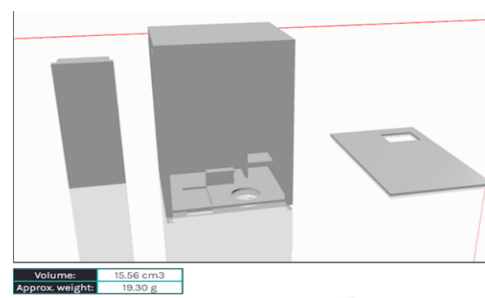


Fig. 11. Weight of the camera enclosure

IV. CONCLUSION

The successful implementation of the smart thermal imaging drone system stands as a testament to its efficacy in the domain of solar power inspection. The seamless integration of the MLX90640 sensor, complemented by a real-time image processing algorithm, positions the system as a sophisticated tool for the identification and analysis of thermal anomalies on solar panels. The innovative application of thermal imaging technology offers a valuable means of early detection, contributing to the overall health and efficiency of solar power installations.

The robust power management incorporated into the system, exemplified by the TP4056 charging module and the 1000mAh LiPo battery, ensures a reliable and sustained power source for extended operational periods. The inclusion of a dynamic switch for toggling between low power mode and full power mode not only optimizes energy consumption during periods of inactivity but also facilitates efficient charging while the system is in standby, ensuring operational readiness.

The protective measures implemented, including circuit protection mechanisms and the 3D-printed weather-resistant housing, further enhance the system's reliability in diverse environmental conditions. This fortification shields the system from potential adversities such as adverse weather conditions, solar radiation, and other environmental stressors, contributing to the longevity and resilience of the overall system.

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